Excitatory Sympathetic Reflex in NaCl-Sensitive Spontaneously Hypertensive Rats

Yoshinari Nakamura, David A. Calhoun, Yiu-Fai Chen, J. Michael Wyss, Suzanne Oparil

We have previously demonstrated blunted reflex responses of lumbar sympathetic nerve activity during volume expansion in NaCl-sensitive spontaneously hypertensive rats maintained on basal (1% NaCl) diets compared with NaCl-resistant spontaneously hypertensive rats, Wistar-Kyoto rats, and Sprague-Dawley rats. The current study tested the hypothesis that chronic ingestion of a high (8%) NaCl diet further blunts cardiopulmonary reflex function in the NaCl-sensitive spontaneously hypertensive rat. After 3 weeks of a 1% or 8% NaCl diet, male rats of all four strains were instrumented with femoral arterial and venous canulas and lumbar nerve recording electrodes at 10 weeks of age. Two days later, conscious rats were infused with whole blood to expand blood volume. NaCl-sensitive spontaneously hypertensive rats maintained on a 1% NaCl diet had blunted responses of nerve activity to acute volume expansion compared with control strains. NaCl-sensitive spontaneously hypertensive rats maintained on an 8% NaCl diet had increases in nerve activity responses to volume expansion. In a second experiment, the volume expansion protocol was repeated in anesthetized NaCl-sensitive spontaneously hypertensive rats that had been subjected to sinoaortic denervation after 3 weeks of a 1% or 8% NaCl diet. After sinoaortic denervation, an increase in nerve activity was again observed during volume expansion in animals fed the 8% NaCl diet. In animals fed the 1% NaCl diet, changes in nerve activity were variable. The excitatory response was significantly reduced after bilateral vagotomy. These studies suggest that blood pressure regulation in NaCl-sensitive spontaneously hypertensive rats is a complex interaction of excitatory and inhibitory sympathetic reflex systems that is altered by high dietary NaCl exposure. (*Hypertension. 1993;22:285-291.*)

**KEY WORDS** • pressoreceptors • hypertension, sodium-dependent • sympathetic nervous system

It has been shown that changes in dietary NaCl influence baroreceptor reflex function in NaCl-sensitive experimental hypertension.1-6 Studies carried out in the Dahl salt-sensitive (Dahl-S) rat indicate that both cardiopulmonary and arterial baroreceptor reflexes are impaired, independent of NaCl intake.7,8 Prehypertensive Dahl-S rats given a low NaCl diet have blunted arterial and cardiopulmonary reflexes compared with Dahl salt-resistant (Dahl-R) rats. The impairment in baroreceptor reflex function in Dahl-S rats is unaffected or exacerbated by increased dietary NaCl ingestion.3-5 In contrast, dietary NaCl supplementation enhances cardiopulmonary and arterial baroreceptor reflex function in Dahl-R rats. Persistent blunting of baroreceptor reflex function in Dahl-S rats may facilitate NaCl-induced increases in blood pressure, whereas enhancement of baroreceptor reflex function would tend to protect Dahl-R rats from NaCl-induced increases in blood pressure.

Reduced sensitivity of cardiopulmonary and arterial baroreceptor reflex function has also been reported in the spontaneously hypertensive rat of the Okamoto strain (SHR). Elevation in arterial pressure or right atrial pressure produces significantly less inhibition of sympathetic nerve activity in SHR than in normotensive controls.9,10 Like the Dahl-S rat, persistent blunting of baroreceptor reflex function may facilitate the development of hypertension in SHR. NaCl-sensitive SHR (SHR-S) (IBU-3 colony, Taconic Farms, Germantown, NY) become hypertensive regardless of diet, but manifest an additional increase in blood pressure associated with increased peripheral sympathetic nervous system activity when maintained on a high NaCl diet.11,12 In contrast, NaCl-resistant SHR (SHR-R) (Charles River, Wilmington, Mass), normotensive Wistar-Kyoto (WKY) rats, and Sprague-Dawley (SD) rats manifest no significant change in blood pressure in response to dietary NaCl supplementation. We have previously demonstrated blunted arterial and cardiopulmonary reflex responses of lumbar sympathetic nerve activity (LSNA) and heart rate (HR) in SHR-S maintained on basal (1% NaCl) diets compared with SHR-R and WKY and SD rats.13,14 After ingestion of a high (8%) NaCl diet, arterial baroreceptor-mediated control of LSNA was no longer blunted in SHR-S during phenylephrine-induced increases in mean arterial pressure (MAP), indicating enhancement of baroreceptor reflex control of LSNA.14 Sensitization of the arterial baroreceptor reflex by dietary NaCl in SHR-S would tend to reduce the severity of NaCl-induced hypertension. Failure of this mechanism to prevent NaCl-induced hypertension suggests that other...
countervailing influences are involved. We hypothesized that one such influence may be persistent blunting of the cardiopulmonary reflex, which has previously been shown by our laboratory to be impaired in SHR-S before high NaCl exposure.\textsuperscript{12} If the cardiopulmonary reflex remained blunted in the SHR-S during dietary NaCl supplementation, it would facilitate the NaCl-induced increase in MAP. The following protocol was designed to test this hypothesis.

Methods

Male SHR-S and normotensive WKY control rats were obtained from Taconic Farms at 7 weeks of age. Male SHR-R and normotensive SD rats were obtained from Charles River Breeding Laboratories at the same age. Rats were maintained four to a cage at constant temperature (24±1°C), humidity (60±5%), and light cycle (12 hours on, 12 hours off). Rats were maintained on either basal (1%) or high (8%) NaCl rat chow (Purina Test Diets, Richmond, Ind). Food and water were available ad libitum throughout the study. All procedures were conducted in accordance with guidelines from The University of Alabama at Birmingham Institutional Animal Care and Use Committee.

Three weeks after initiation of basal (1%) or high (8%) NaCl diets, rats were anesthetized with pentobarbital sodium (60 mg/kg IP) for placement of femoral arterial and venous cannulas and lumbar nerve electrodes. The femoral artery and vein were cannulated with PE-10 fused to PE-50 tubing for blood pressure monitoring and intravenous infusion of blood, respectively. The cannulas were exteriorized between the scapulae. After laparotomy, the lumbar sympathetic nerve on the left side was isolated and freed of fat and connective tissue. Bipolar stranded stainless steel electrodes (Medwire, Mt Vernon, NY) were placed around the nerve for multifiber nerve recording. The electrodes were connected by a high gain impedance probe (model P511, Grass Instrument Co, Quincy, Mass) to a Grass P511 preamplifier, where the signal was amplified (×20 000) and filtered (low frequency, more than 30 Hz; high frequency, less than 1000 Hz). The modified signal was fed into an oscilloscope (model 5113, Tektronix, Beaverton, Ore) and Grass AM8 audio monitor for evaluation. When an optimal signal was achieved, the electrodes were fixed in place with silicone cement (Wacker Sil Gel 604, Wacker-Chemie Gimble, Munich, Germany). The electrode wires were externalized between the scapulae and fixed in place with dental cement along with the catheters. The abdominal incision was then closed.

Two days later, after measurement of body weight, freely moving animals had their arterial cannulas connected to a CP-02 pressure transducer (Century Technology, Inglewood, Calif) for recording of arterial pressure on a Grass model 7 polygraph. HR was monitored by a cardiostethometer (Grass 7P44C) triggered by the systolic pressure rise. The signal from the lumbar recording electrodes was amplified and filtered as above and then rectified and integrated over 1-second intervals (Grass 7P10) before recording on the polygraph. The quality of the nerve signal was assessed with an intravenous injection of norepinephrine (5 μg). Significant inhibition of nerve activity indicated a good signal. MAP, HR, and LSNA were recorded throughout each experiment.

To assess the reflex-mediated response to volume expansion, MAP, HR, and LSNA were recorded during an infusion of whole blood that expanded blood volume by 15% within 6 minutes. The volume of blood to be infused was calculated on the basis of 7% of body weight, estimating total blood volume as determined in our laboratory (unpublished data). Whole human blood collected from healthy normotensive donors was used for volume expansion. From each individual, 8 mL blood was drawn into a heparinized test tube and pooled with blood collected from several other donors. The pooled blood was kept at 37°C in an open test tube for at least 15 minutes before administration. Each experiment consisted of a 30-minute control period, in which all parameters were stabilized, followed by volume expansion, as described above. After the protocol was completed, the rat was killed by an overdose of sodium pentobarbital, and postmortem LSNA was recorded for 30 minutes. Postmortem LSNA was subtracted from all measured LSNA values.

All values are expressed as mean±SEM. LSNA is expressed as percentage of change from nerve activity during the control period. To compare the baroreceptor reflex-mediated response to volume expansion among the eight groups, MAP, HR, and LSNA were compared at control and at 5%, 10%, and 15% volume expansion by analysis of variance followed by the Student-Newman-Keuls multiple comparison test. The curves relating LSNA, change in HR, and change in MAP to percentage of volume expansion were analyzed by linear regression for each rat during volume expansion. A mean slope was calculated for each relation for each strain-diet group. The slopes of these regression lines were compared by two-way analysis of variance, followed by Student-Newman-Keuls multiple comparison test. Body weight and control MAP and HR values were compared using the same statistical methods. In all statistical tests, significance was attained if \( P<.05 \).

In an effort to localize the origin of the excitatory reflex, the infusion protocol was repeated after bilateral sinoaortic denervation (SAD) in SHR-S maintained on 1% or 8% NaCl diet. The animals were initially anesthetized with sodium methohexitol (70 mg/kg IP) for placement of femoral arterial and venous cannulas. Further anesthesia was then achieved with an intravenous bolus injection of urethane (25 mg/kg) and α-chloralose (50 mg/kg). Additional boluses of α-chloralose (10 to 25 mg/kg) were given as needed during the experiment to maintain a constant level of anesthesia. This combination of anesthetics was chosen to provide adequate anesthesia and analgesia with minimal effect on cardiovascular and baroreceptor reflex function.\textsuperscript{2,3} After placement of lumbar nerve recording electrodes and verification of signal quality by significant suppression of LSNA after intravenous injection of norepinephrine (5 μg), a ventral midline incision was made in the neck, and the trachea was cannulated. The left carotid bifurcation was exposed, the superior laryngeal and the aortic depressor nerves were sectioned, and the superior cervical ganglion was removed as originally described by Krieger.\textsuperscript{15} Any remaining carotid baroreceptor afferents were destroyed by stripping the carotid bifurcation and painting with 10% phenol. This proce-
dure was then repeated on the right side. Effectiveness of the SAD procedure was confirmed by absence of LSNA suppression during norepinephrine-induced increases in MAP (30 to 40 mm Hg). A PE-10 polyurethane cannula was inserted into the superior vena cava via the right internal jugular vein to the level of the right atrium. The right atrial catheter was then connected via a CP-02 pressure transducer to a Grass model 7 polygraph for recording of right atrial pressure. After a 30-minute stabilization period, the infusion protocol was done as above. Body temperature was maintained at 37° to 38°C throughout the surgical preparation and experimental protocol with use of a variable temperature heating pad.

In four of the SAD animals maintained on 8% NaCl diet after completion of the whole blood infusion protocol, blood equal in volume to the previously infused amount was removed from the animal via the central arterial catheter. After stabilization of MAP, the infusion protocol was repeated using dextran 40.

The above infusion protocol was also repeated in five SHR-S fed 8% NaCl diet before and after bilateral vagotomy. After anesthesia and placement of lumbar recording electrodes as above, animals were infused with dextran 40 to expand blood volume (15% of estimated blood volume) over 6 minutes. Blood equal in volume to the infused dextran was then removed. After tracheostomy, the right and left vagus nerves were ligated at the level of the common carotid artery. Thirty minutes after vagotomy, animals were again infused with dextran 40 to expand blood volume (15% of estimated blood volume) over 6 minutes. The magnitude of the LSNA response to volume infusion was compared before and after vagotomy.

**Results**

SD rats fed either diet were heavier than any other diet-strain group (Table 1). SHR-S and SHR-R did not differ in weight, but both groups were significantly lighter than WKY or SD rats. The high NaCl diet had no significant effect on weight gain in any strain. MAP was not significantly different in the two hypertensive strains on the basal NaCl diet but was significantly higher in SHR-S and SHR-R than in the two normoten­

<table>
<thead>
<tr>
<th>Diet/Strain</th>
<th>n</th>
<th>Body weight (g)</th>
<th>MAP (mm Hg)</th>
<th>HR (bpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. SHR-S 1%</td>
<td>8</td>
<td>249.7±3.4EG</td>
<td>129.9±4.8BEG</td>
<td>403.1±16.3</td>
</tr>
<tr>
<td>B. SHR-S 8%</td>
<td>10</td>
<td>239.5±4.3DPN</td>
<td>159.2±4.9DPH</td>
<td>402.2±12.2</td>
</tr>
<tr>
<td>C. SHR-R 1%</td>
<td>7</td>
<td>247.6±6.9DPN</td>
<td>127.6±2.8EG</td>
<td>402.8±21.4</td>
</tr>
<tr>
<td>D. SHR-R 8%</td>
<td>7</td>
<td>245.6±4.9DPN</td>
<td>129.8±3.2DPH</td>
<td>403.0±19.3</td>
</tr>
<tr>
<td>E. WKY 1%</td>
<td>6</td>
<td>275.6±5.4ACG</td>
<td>105.0±6.0AC</td>
<td>390.8±19.6</td>
</tr>
<tr>
<td>F. WKY 8%</td>
<td>6</td>
<td>283.7±10.1BDO</td>
<td>112.5±5.3RD</td>
<td>383.3±18.2</td>
</tr>
<tr>
<td>G. SD 1%</td>
<td>9</td>
<td>316.3±17.2AC</td>
<td>110.6±4.2AC</td>
<td>419.4±18.0</td>
</tr>
<tr>
<td>H. SD 8%</td>
<td>5</td>
<td>310.0±9.2BDF</td>
<td>106.0±3.1RD</td>
<td>392.0±13.5</td>
</tr>
</tbody>
</table>

MAP, mean arterial pressure; HR, heart rate; bpm, beats per minute; SHR-S, NaCl-sensitive spontaneously hypertensive rats; SHR-R, NaCl-resistant spontaneously hypertensive rats; WKY, Wistar-Kyoto rats; SD, Sprague-Dawley rats. Values are mean±SEM. Capital letters behind each value represent significant differences (P<.05) between body weight, MAP, and HR for that group vs the group (or groups) indicated by the letter.

Volume expansion was associated with progressive decreases in LSNA in SHR-R, WKY, and SD rats on a basal NaCl diet, but not in SHR-S (Fig 1). LSNA expressed as a percentage of control was significantly greater in SHR-R fed a basal NaCl diet than in SHR-R, WKY, or SD rats at 5%, 10%, and 15% volume expansion. The slope of the LSNA–volume expansion relation for SHR-S on a basal diet was significantly greater (less negative) than in the other three strains (Table 2). High NaCl feeding was not associated with significant changes in the slopes of the LSNA–volume infused relations in WKY or SD rats.

Volume expansion was associated with a progressive increase in LSNA in SHR-S fed a high NaCl diet (Fig 1). At 5%, 10%, and 15% volume expansion, LSNA was significantly above baseline, consistent with a positive feedback type reflex.

HR decreased significantly in response to volume expansion in all diet-strain groups except SHR-S fed 1% NaCl diet (Fig 1). In SHR-S fed 1% NaCl diet, HR was not significantly different from baseline values at any time during volume expansion. Change in HR from baseline values expressed as beats per minute was significantly less in SHR-S fed a basal NaCl diet than in SHR-R, WKY, or SD rats at 5%, 10%, and 15% volume expansion; the latter three groups were not significantly different from one another. Further, the slope of the HR–volume infused relation was significantly greater (less negative) in SHR-S than in the other three strains on either diet. The high NaCl diet did not significantly affect the slope of the HR–volume expansion relation in any strain (Table 2).

MAP increased during volume expansion in SHR-S, SHR-R, and WKY rats ingesting both basal and high NaCl diets but only in SD rats maintained on 8% NaCl diet (Fig 1). MAP expressed as absolute change from baseline (in millimeters of mercury) was not significantly different in SHR-S, SHR-R, and WKY rats at 5%, 10%, and 15% volume expansion, independent of diet, and the slopes of the MAP–volume infused relation did not differ significantly among these three groups. The slope of the MAP–volume infused relation
FIG 1. Line graphs show changes in lumbar sympathetic nerve activity (LSNA), heart rate (HR), and mean arterial pressure (MAP) during volume expansion. Estimated volume expansion of 5%, 10%, and 15% occurred at 2, 4, and 6 minutes after beginning the infusion of whole blood. n=8 for SHR-S, 1% NaCl group; n=10 for SHR-S, 8% NaCl group; n=7 for SHR-R, 1% NaCl and 8% NaCl groups; n=6 for WKY rats, 1% NaCl and 8% NaCl groups; n=9 for SD rats, 1% NaCl group; n=5 for SD rats, 8% NaCl group. *Significant differences (P<.05) of the slopes of the regression lines of SHR-S vs the other three groups (two-way ANOVA). #Significant differences (P<.05) of the slopes of the regression lines among SHR-R, WKY, and SD rats. ^Represents significant differences (P<.05) of the slopes of the regression lines of SD rats vs the other three groups.

Mean body weights of the 1% and 8% SHR-S subjected to SAD were similar (Table 3). MAP after SAD was significantly lower in the 1% SHR-S than in the 8% SHR-S (135±5 vs 166±5 mm Hg, P<.05). Mean right atrial pressure after SAD was similar in 1% and 8% SHR-S (2.5±0.4 vs 2.6±0.3 mm Hg, respectively). MAP and right atrial pressure increased progressively with volume expansion in both groups of SAD animals (Fig 2). HR did not change in 1% SHR-S during volume expansion but did increase in 8% SHR-S (Fig 2). Changes in LSNA were small and variable in 1% SHR-S during volume expansion after SAD, with the overall effect not significantly different from baseline in any strain-diet group. Dietary NaCl supplementation was associated with a significant increase in the slope of the MAP-volume infused relation in this strain only.
**TABLE 3. Baseline Characteristics of Sinoaortic-Denervated NaCl-Sensitive Spontaneously Hypertensive Rats Maintained on 1% or 8% NaCl Diet**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1% NaCl (n=8)</th>
<th>8% NaCl (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (g)</td>
<td>239±3</td>
<td>245±5</td>
</tr>
<tr>
<td>Mean arterial pressure (mm Hg)</td>
<td>135±5*</td>
<td>166±5</td>
</tr>
<tr>
<td>Heart rate (bpm)</td>
<td>452±9</td>
<td>439±11</td>
</tr>
<tr>
<td>Right arterial pressure (mm Hg)</td>
<td>2.5±0.3</td>
<td>2.6±0.3</td>
</tr>
</tbody>
</table>

bpm, Beats per minute. Values are mean±SEM.

*P<.05 significantly different from NaCl-sensitive spontaneously hypertensive rats given 8% NaCl diet.

In contrast, increases in LSNA during volume infusion were observed consistently in 8% SHR-S after SAD. This increase in LSNA was also observed in the SAD animals in which the volume expansion was repeated with dextran instead of whole blood, suggesting that stimulation of the excitatory reflex was not due to a vasoactive substance in whole blood.

The mean body weight of the 8% SHR-S subjected to vagotomy was 252±2 g. MAP tended to be lower before than after vagotomy, but the difference was not statistically significant (151±10 vs 179±16 mm Hg, before vs after vagotomy). HR before vagotomy was significantly lower than after vagotomy (395±12 vs 459±12 beats per minute, before vs after vagotomy, P<.05). Before vagotomy, volume infusion resulted in significant increases in MAP and LSNA (Fig 3). After vagotomy, the volume-induced increases in MAP and LSNA were significantly different from baseline and from before-vagotomy values. HR was not significantly different from baseline either before or after vagotomy.

**Discussion**

The principal finding of the present study is that dietary NaCl supplementation is associated with an increase in LSNA during acute volume expansion in SHR-S maintained on high dietary NaCl but not in SHR-S on a basal NaCl diet or in SHR-R, WKY, or SD rats on either a basal or high NaCl diet. Such an increase in sympathetic nerve activity during volume expansion is characteristic of previously described cardiovascular excitatory sympathetic reflexes.16-19 Work done in cats and dogs suggests that cardiovascular excitatory reflexes originate from afferent sensory endings in the atria, ventricles, aorta, and the pulmonary vasculature.20-26 These reflexes are positive feedback in nature and serve to increase blood pressure, whereas sinoaortic negative feedback systems act simultaneously to decrease blood pressure. Thus, blood pressure regulation as mediated by the sympathetic nervous system involves a complex interplay of inhibitory and excitatory cardiovascular reflexes that operate in counterregulatory fashion. The present study suggests that (1) blood pressure regulation in NaCl-sensitive SHR, as in cats and dogs, is a function of both inhibitory and excitatory reflex systems and (2) NaCl-induced increases in blood pressure in SHR are related to alteration of this complex interaction of excitatory and inhibitory reflexes.

The current study is the first demonstration of excitatory sympathetic reflexes in SHR. Previous work char-
characterizing pressor reflexes has been limited to cats and dogs. Investigators conducting volume infusion experiments in other rodent models of hypertension have not reported excitatory responses such as we observed in the SHR-S. Explanation for this may include differences in methodology, including the type, volume, and rate of infusion; the particular nerve used to record sympathetic nerve activity; or strain differences. Defects in baroreceptor reflex function have been localized to different components of the baroreceptor reflex arc depending on the strain studied. Baroreceptor reflex abnormalities in the Dahl rat have been localized to the peripheral baroreceptor, whereas baroreceptor reflex abnormalities in the SHR are thought to be more centrally located. The relative roles or even the presence of excitatory sympathetic reflexes may likewise vary between species or strains.

The present study suggests that the NaCl-induced increase in blood pressure in SHR-S is related to alteration of the interaction of excitatory and inhibitory sympathetic reflexes. The increase in LSNA after volume expansion was observed in conscious SHR-S maintained on a high NaCl diet and not in SHR-S maintained on a basal diet or in SHR-R, WKY, or SD rats on either diet. We hypothesize that NaCl exposure had the effect of increasing the contribution of the excitatory reflex relative to the inhibitory baroreceptor reflex. This could have been accomplished by blunting of the cardiopulmonary inhibitory reflex to the extent that the excitatory reflex was unmasked. Alternatively, high dietary NaCl exposure could have enhanced the excitatory reflex such that it predominated over the cardiopulmonary baroreceptor reflex. Additional studies are needed to differentiate between these two possibilities.

In SHR-S fed the 8% NaCl diet, the excitatory response was not altered by sinoaortic denervation, indicating that it was not transmitted via the sinoaortic baroreceptor reflex pathway. The response was eliminated by bilateral vagotomy, suggesting that the response originates from vagal afferents and not from sinoaortic baroreceptors. This is in contrast to data in dogs and cats suggesting that the excitatory response originates from sympathetic afferent endings in the heart, aorta, and pulmonary vasculature. In SHR-S fed the 8% NaCl diet, HR was unaffected or minimally suppressed by acute volume expansion. After sinoaortic denervation, the HR remained unchanged in 1% SHR-S during volume expansion but increased significantly in 8% SHR-S, suggesting that HR control in SHR-S, like blood pressure, is a combination of excitatory and inhibitory reflexes. In the absence of sinoaortic baroreceptor reflex function and after high dietary NaCl exposure, the excitatory response predominates. In contrast, in cats and dogs stimulation of sympathetic excitatory reflexes produces a tachycardiac response even with the counterregulatory effects of the sinoaortic baroreceptor reflex left intact. This difference suggests that the inhibitory reflexes play a more dominant role than the excitatory reflexes in HR control in SHR regardless of dietary NaCl exposure. Excitatory reflexes predominate and a tachycardiac response is observed only with deactivation of the inhibitory reflexes.

In summary, previous studies from our laboratory and others have demonstrated decreased cardiopulmonary reflex activity, assessed during acute volume expansion or chemical stimulation, in SHR, in hypertensive Dahl rats, and in rabbits with renal hypertension. Although blunted, the cardiopulmonary reflex response was still inhibitory. The current study is the first demonstration of an excitatory reflex response to volume expansion in SHR. We hypothesize that high dietary NaCl exposure had the effect of shifting the interaction between the excitatory and the inhibitory reflex systems toward the excitatory response. The consequence of such a response would be an increase in sympathetic tone and, thereby, an increase in blood pressure.

Acknowledgments

This work has been supported in part by grants HL-22544, HL-37722, and HL-47081 from the National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Md. Dr Calhoun is a recipient of a Physician-Scientist Award.
(HL-02568) from the National Heart, Lung, and Blood Institute and is supported by a Research Project grant from the Southern Medical Association.

References


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doi: 10.1161/01.HYP.22.3.285

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1993 American Heart Association, Inc. All rights reserved.
Print ISSN: 0194-911X. Online ISSN: 1524-4563

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