Dietary salt intake alters cardiovascular responses evoked from the rostral ventrolateral medulla

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Ito, Satoru, Frank J. Gordon, and Alan F. Sved. Dietary salt intake alters cardiovascular responses evoked from the rostral ventrolateral medulla. Am. J. Physiol. 276 (Regulatory Integrative Comp. Physiol. 45): R1600–R1607, 1999.—The present experiments examined whether in rats consuming diets with either high NaCl content (8%) or low Na+ content (0.01%) for 2 wk excitatory inputs to the rostral ventrolateral medulla (RVLM) would be altered. In chloralose-anesthetized rats, injection of glutamate into the RVLM elicited a pressor response that, compared with rats fed a control diet, was 50% larger in rats fed a diet containing 8% NaCl and was 25% smaller in rats fed a diet containing 0.01% Na+. Pressor responses produced by electrical stimulation of sciatic nerve afferents, as well as by microinjections into the RVLM of L-dihydroxyphenylalanine or carbachol, were all potentiated by high dietary salt intake and reduced by low dietary salt intake. Dietary salt intake had no effect on pressor responses produced by intravenous injection of phenylephrine, indicating that salt-related alterations in cardiovascular responses produced by central activation could not be accounted for by changes in peripheral vascular reactivity. The decrease in arterial pressure produced by injection of glutamate into the nucleus of the solitary tract was also potentiated by the high salt diet, suggesting that the sensitivity of central baroreceptor reflex pathways may be altered by dietary NaCl. These results indicate that the amount of NaCl consumed in the diet can change the sensitivity of RVLM sympatoexcitatory neurons, and this change in sensitivity is not restricted to any particular class of cell surface receptors.

excitatory amino acid; somatic pressor response; baroreceptor reflex; hypertension; arterial blood pressure

EXCESS DIETARY SALT is a contributing factor to the pathogenesis of hypertension (4, 20). Although high salt intake does not invariably lead to an elevation in arterial blood pressure (AP), a number of conditions, including genetic ones, can predispose individuals to salt-sensitive elevations in AP. High dietary salt intake is a necessary component for the development of some forms of experimental hypertension, including DOCA-salt hypertension (7), Dahl genetic salt-sensitive hypertension (24), and one-kidney, renal wrap hypertension (10). Moreover, excess salt exacerbates hypertension in several animal models (1, 18, 21, 25, 34). Although the mechanism(s) by which high dietary salt produces or augments hypertension have not been clearly elucidated, a neurogenic component likely plays an important role because elevated sympathetic vasomotor tone is associated with salt-sensitive hypertension in both animal models and humans (4, 20).

Because the activity of peripheral sympathetic nerves is controlled by the central nervous system (CNS), it has often been suggested that increased dietary salt might affect CNS neuronal circuits that regulate sympathetic control of cardiovascular function (2, 19, 26, 31). A role for brain mechanisms in increased sympathoexcitation associated with elevated dietary salt intake received strong support from a study by Pawloski-Dahm and Gordon (22). In these experiments, rats drinking 0.9% NaCl instead of water showed greater increases in AP in response to injection of the excitatory amino acid (EAA) L-glutamate (Glu) into the rostral ventrolateral medulla (RVLM). The RVLM contains “vasomotor” cells that provide the major descending excitatory input to spinal sympathetic preganglionic neurons that govern sympathetic vasomotor outflow (6, 9). Pawloski-Dahm and Gordon (22) suggested that salt-induced sensitization of RVLM neurons might predispose toward the development of hypertension. However, because only a single stimulus (i.e., Glu) was used to activate RVLM neurons in these studies, the question of whether excess dietary salt augments RVLM responses elicited only by direct glutamatergic excitation, or alternatively, produces a more generalized functional change in RVLM sensitivity was not determined. If salt-induced RVLM sensitization is specific for Glu stimulation, this result would implicate a particular neurotransmitter/receptor system in the central neurogenic effects of salt. If, on the other hand, augmented RVLM responses could be produced by a diverse range of stimuli, this result would suggest that excess salt intake might affect the cellular properties of RVLM neurons themselves or a particular afferent system to the RVLM that alters the responsiveness of RVLM neurons to all inputs. One of the principal aims of the present experiments was to distinguish between these two possibilities. A second question addressed by these studies was whether the amount of salt consumed in the diet might influence the function of RVLM sympatoexcitatory neurons. To examine this question, central cardiovascular responses were measured under conditions of dietary salt restriction as well as supplementation.

METHODS

Experiments were conducted on adult male Sprague-Dawley rats (Zivic Laboratories, Zelienople, PA). Rats were housed singly in wire mesh cages in a temperature-controlled room on a 12:12-h light-dark cycle with Purina Lab Chow (1% NaCl) and tap water available ad libitum for at least 1 wk. Rats were then assigned to one of three dietary groups. Each
diet was based on a formulation containing 0.01% Na\(^+\) (TD 90228, Harlan Teklad, Madison, WI) and supplemented with either 1% NaCl (control diet), 8% NaCl (high-salt diet), or no additional Na (low-salt diet). Water was available ad libitum throughout. Rats weighed 260–340 g when they were placed on one of the test diets; there was no significant difference among the groups of rats at the beginning of this period. Body weight was measured every 4–5 days. Rats remained on the test diet 14 days, at which time they were prepared for brain stem injections as previously described (13). Briefly, rats were anesthetized with 2% halothane mixed in 100% \(O_2\) administered through a cone placed over the nose. A cannula (PE-50 tubing filled with heparinized saline) was inserted into the right femoral artery for recording of mean AP (MAP) and heart rate (HR). A second cannula was placed in the right femoral vein for drug administration. The trachea was cannulated, and rats were artificially ventilated with 2% halothane in 100% \(O_2\) followed by the administration of a muscle relaxant (o-tubocurarine, 0.5 mg/kg iv, supplemented hourly with 0.2 mg/kg iv).

Rats were placed in a stereotaxic instrument with the incisor bar positioned 11 mm below the interaural line. The dorsal surface of the medulla was exposed by limited craniotomy, and the area postrema was visualized. Chloralose was administered (60 mg/kg iv, supplemented hourly with 20 mg/kg iv), and the halothane was terminated. Rats were ventilated with 100% \(O_2\) throughout the remainder of the experiment. After the completion of all surgical manipulations, animals were left to stabilize for at least 20 min before the start of the experiment. In a subset of animals on each test diet, blood volume was measured by dye dilution using Evans blue dye (27, 32) just before brain stem surgery.

Injections of drugs were made into the brain stem, as previously described (13), using single-barrel glass micropipettes. All drugs were dissolved in artificial cerebrospinal fluid (aCSF; in mM: 144 NaCl, 1.2 CaCl\(_2\), 2.8 KCl, and 0.9 MgCl\(_2\)) and injected in a 100-nl volume over a period of 2–5 s using a PicoPump (WPI, New Haven, CT). For bilateral injections, an injection was made on one side of the medulla, the pipette was withdrawn from the brain and positioned on the contralateral side, and the contralateral injection was made. The two injections were made ~1 min apart. In most animals, injections of multiple drugs or doses of drugs were tested. Before each injection, baseline AP and HR were recorded for at least 10 min. In most experiments in which the effects of a drug injected unilaterally were examined, the response to the drug was first tested on the right side and later tested on the left side; these two responses were averaged to provide a single measure for each animal. Coordinates for RVLM sites used in this study were, relative to the caudal tip of the area postrema and with the pipette angled 20° rostral, 1.6–2.0 rostral, 1.9 mm lateral, and 3.2 mm ventral. Coordinates for microinjections into the nucleus of the solitary tract (NTS) were (with the pipette vertical) 0.5 mm lateral and 0.5 mm rostral to the caudal tip of the area postrema and 0.5 mm below the dorsal surface of the brain stem.

The response to Glu injected into the RVLM was tested over a range of doses (33, 100, 330, and 1,000 pmol) with two to three doses tested in each rat. Doses were tested in random order, with at least 15 min between injections. Responses to carbacool (100 pmol) and dihydroxyphenylalanine (DOPA) (1.5 nmol) were tested in separate groups of rats; doses represent the midrange of the dose-response curve on the basis of published reports (17, 33, 35). Effects of injections into the NTS of Glu (50 or 200 pmol) or nipecotic acid were tested in other groups of rats.

Electrical stimulation of the sciatic nerve was performed as described by Kiely and Gordon (16). The left sciatic nerve was identified and placed on a bipolar stainless steel wire electrode (Teflon-coated, 3-stranded, stainless steel wire; A-M Systems, Everett, WA), and the electrodes were isolated and secured in place using polyvinyl siloxane dental impression material (Cobelte, Kent Dental). Square-wave stimuli (10-s train of 1 ms 250-µA pulses at 20 Hz) were delivered from a Grass S88 stimulator equipped with a stimulus isolation unit.

At the conclusion of most experiments, ~20 nl of 1% Fast Green was injected into the RVLM using the same micropipette that was previously used for drug injections to mark the location of the injection sites. Animals were then decapitated, and the brain stem was rapidly removed and frozen in isopentane on dry ice. Brain stems were subsequently cut into 40-μm sections using a cryostat, and sections were mounted on glass microscope slides and stained with neutral red. RVLM injection sites were similar to those previously published by our laboratories (13, 16) and were located ventral to the compact portion of the nucleus ambiguus at the rostral-caudal plane corresponding to 2.8 mm from intra-aural on the basis of the atlas of Paxinos and Watson (23).

Data are expressed as means ± SE and were analyzed by ANOVA followed by the Newman-Keuls test (Statistica, StatSoft). Experiments were typically analyzed by two-way ANOVA (dietary group as 1 factor and change in MAP as the other factor, with or without dose as a repeated measure). The relationships between measured cardiovascular responses and dietary salt content were also assessed by linear regression analysis. Differences among treatments were determined to be significantly different if \(P < 0.05\).

**RESULTS**

Rats gained weight steadily during the 14 days on the different diets, although rats eating the 0.01% NaCl diet gained weight more slowly. At the end of the 14-day period, rats on the low-salt diet weighed significantly less than rats on the high-salt diet, although neither of these groups was different from the control diet group (Table 1). MAP and HR were similar in the three groups of rats (Table 1). Blood volume relative to body weight was increased by ~10% in rats that had been on the high-salt diet for 14 days compared with rats on the other diets (Table 1).

Injection of Glu unilaterally into the RVLM of rats consuming the three diets elicited dose-related increases in mean arterial pressure (MAP) and heart rate (HR) in rats fed low-salt diet (n = 18), 1.0% salt diet (n = 14), or 8.0% salt diet (n = 16). Blood volume was measured in a subset (n = 4) of rats fed each diet. *Significant difference from 1% salt group, \(P < 0.05\). †Significant difference from 0.01% Na\(^+\) group, \(P < 0.05\).

<table>
<thead>
<tr>
<th>Dietary Salt</th>
<th>Body weight (g)</th>
<th>MAP (mmHg)</th>
<th>HR (beats/min)</th>
<th>Blood Volume (ml/100 g body wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01% Na(^+)</td>
<td>360 ± 8</td>
<td>118 ± 3</td>
<td>389 ± 11</td>
<td>19.5 ± 0.7*</td>
</tr>
<tr>
<td>1.0% NaCl</td>
<td>388 ± 7</td>
<td>114 ± 3</td>
<td>356 ± 6</td>
<td>23.6 ± 0.8</td>
</tr>
<tr>
<td>8.0% NaCl</td>
<td>399 ± 11</td>
<td>111 ± 2</td>
<td>367 ± 7</td>
<td>26.6 ± 0.6†</td>
</tr>
</tbody>
</table>

Values are means ± SE. Values for mean arterial pressure (MAP) and heart rate (HR) are initial baseline values for rats fed low-salt diet (n = 18), 1.0% salt diet (n = 14), or 8.0% salt diet (n = 16). Blood volume was measured in a subset (n = 4) of rats fed each diet.

Table 1. MAP, HR, body weight, and blood volume in rats that had been consuming diets with a normal, high, or low salt content for 2 wk.
creases in AP (Fig. 1). The magnitude of these pressor responses was dependent on the salt content of the diet (Fig. 1). Compared with the normal salt diet, pressor responses elicited by 1 nmol of Glu in rats on the high-salt diet were increased by ~50%, whereas pressor responses were reduced by ~25% in rats consuming the low-salt diet. Changes in HR elicited by injection of Glu into the RVLM were inconsistent and not significantly different across groups (data not shown).

To determine whether dietary salt-related differences in pressor responses evoked by exogenous Glu injected into the RVLM would also be observed when RVLM neurons were activated by synaptic release of Glu, we measured pressor responses produced by sciatic nerve stimulation. We previously showed this response to require EAA acid-mediated neural transmission in the RVLM (16). Similar to what was observed with exogenous Glu, the pressor response elicited by sciatic nerve stimulation was markedly potentiated in rats on the high-salt diet and reduced in rats on the low-salt diet (Fig. 2). Furthermore, the extent to which the sciatic nerve response was altered by the high- and low-salt diets was similar to that seen with exogenous Glu. Sciatic nerve stimulation was accompanied by a significant tachycardia, and the magnitude of this response was related to the salt content of the diet (Fig. 2).

To determine whether the salt-induced changes in the magnitude of RVLM responses were specifically related to activation of RVLM neurons by EAAs or instead reflected a general increase in the excitability of these neurons, we measured RVLM pressor responses evoked by drugs that produce their actions independently of EAA receptors. Carbachol injected
into the RVLM was previously shown to increase MAP via an action on cholinergic muscarinic receptors (8, 33). Carbachol (100 pmol) injected unilaterally into the RVLM produced a pressor response in rats consuming the diet with a normal salt content (Fig. 3). This response was enhanced in rats on the 8% salt diet and reduced in the rats on the low-salt diet (Fig. 3), similar to what was observed with Glu. Injection of L-DOPA into the RVLM was also reported to increase MAP, via a mechanism unrelated to its possible conversion to catecholamines (17, 35). Unilateral injection of DOPA (1.5 nmol) into the RVLM evoked a pressor response that was also increased in rats consuming the high-salt diet and reduced in rats on the low-salt diet (Fig. 3).

In addition to direct excitation, the activity of RVLM neurons can also be increased by removing tonic inhibition. One means by which to produce this disinhibition is by injection of the GABA uptake inhibitor nipecotic acid into the NTS (5). Increased GABAergic inhibition within the NTS would be expected to reduce the firing of inhibitory interneurons in the caudal ventrolateral medulla that control the activity of RVLM sympathoexcitatory neurons (28), thus resulting in large increases in AP (5). Thus, to determine whether pressor responses produced by disinhibition of the RVLM are also influenced by dietary salt intake, we injected nipecotic acid into the NTS. Bilateral injections of nipecotic acid (10 nmol) into the NTS increased MAP in rats consuming each of the diets (Fig. 4). Compared with rats consuming the normal salt diet, this response was significantly attenuated in rats fed the low-salt diet; although the response was not significantly greater in the rats fed the high-salt diet compared with control, there was still a highly significant correlation between dietary salt content and the increase in MAP elicited by injection of nipecotic acid into the NTS ($r = 0.69$, $P < 0.01$).

Excitation of the NTS elicits a decrease in MAP by increasing the activity of an inhibitory input to the RVLM and reducing the activity of RVLM sympathoexcitatory neurons (28). To determine the influence of dietary salt content on this inhibitory response and to test the hypothesis that high salt intake may attenuate this response due to enhanced responsiveness to excitatory inputs, the depressor response to injection of Glu into the NTS was tested in rats on the different diets. In rats fed the normal salt diet, injection of 200 pmol Glu (a maximally effective dose; Ref. 30) into the NTS decreased MAP $\sim 40$ mmHg, whereas injection of 50 pmol produced a response that was approximately half maximal, as expected (14). In rats fed the high-salt diet, the response to 50 pmol was significantly enhanced compared with the other groups (Fig. 5). There was no significant difference in this depressor response between rats fed the low-salt diet and the normal salt diet. The larger dose of Glu injected into the NTS produced a depressor response of $\sim 40$ mmHg in each group (Fig. 5), consistent with the fall in MAP elicited by total blockade of autonomic transmission (see below). Glu injected into the NTS elicited a dose-related bradycardia that was similar in all groups (Fig. 5).

![Fig. 3. Effect of dietary salt intake on change in MAP elicited by injection of carbachol (A) or dihydroxyphenylalanine (DOPA; B) into RVLM. Change in MAP and HR in response to injection of carbachol (100 pmol) or DOPA (1.5 nmol) unilaterally into RVLM was tested in different groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% salt for previous 14 days ($n = 4–6$). Carbachol elicited a significant increase in MAP in animals on the 1% salt diet ($* P < 0.05$); this response was significantly greater in rats on 8% salt diet ($* P < 0.05$) and rats on 0.01% salt diet did not show a significant increase in MAP in response to carbachol injection. Carbachol did not elicit a significant change in HR in any groups. DOPA elicited a significant increase in MAP in animals on the 1% salt diet ($* P < 0.05$); this response was significantly greater in rats on 8% salt diet ($* P < 0.05$) and rats on 0.01% salt diet did not show a significant increase in MAP in response to carbachol injection. Carbachol did not elicit a significant change in HR in any groups. DOPA elicited a significant increase in MAP in each group; compared with response in rats on 1% salt diet, response was significantly enhanced in rats on 8% salt diet ($* P < 0.05$) and significantly reduced in rats on 0.01% salt diet ($* P < 0.05$). In rats on 1% salt diet, injection of DOPA into RVLM did not alter HR ($\pm 3$ beats/min) and a similar lack of response was observed in rats on low-salt diet ($\pm 4$). In contrast, injection of DOPA into RVLM of rats on high-salt diet elicited a consistent and significant bradycardia ($\pm 8$ beats/min; $P < 0.05$ compared with other groups).
To determine whether differences in pressor responses observed between the groups of rats consuming the different diets resulted from differences in vascular reactivity, we examined the increase in MAP elicited by intravenous injection of the $\alpha_1$-adrenergic agonist phenylephrine. To eliminate the baroreflex buffering of phenylephrine-evoked vasoconstriction, the responses to phenylephrine were measured in rats that had been pretreated with hexamethonium (30 mg/kg iv). Ganglionic blockade lowered blood pressure by a similar degree in all three groups of rats (MAP at 10 min after injection of hexamethonium: low salt $242 \pm 6$ mmHg, normal salt $252 \pm 6$ mmHg, and high salt $249 \pm 6$ mmHg, $P < 0.05$). However, after ganglionic blockade, MAP in the rats on the high-salt diet was maintained at a lower level than MAP in the other groups ($P < 0.05$; Fig. 6), and blood pressure after ganglionic blockade was significantly inversely correlated with dietary salt intake ($r = 0.78$, $P < 0.01$). Nonetheless, the dose-response curves for phenylephrine-induced increases in MAP in the three groups were the same (Fig. 7).

**DISCUSSION**

Pressor responses evoked by injection of Glu into the RVLM of chloralose-anesthetized rats were enhanced in rats with a high dietary consumption of NaCl (8% NaCl in diet, intake of $\sim 35$ meq/day for 2 wk) compared with rats eating a standard diet containing 1% NaCl (~4.4 meq/day). This observation is similar to data reported previously by Pawloski-Dahm and Gordon (22), showing an enhanced pressor response to Glu injected into the RVLM of urethan-anesthetized rats after 2 wk of elevated salt intake due to inclusion of 0.9% NaCl in the drinking water. However, Tsuji et al. (29) reported that pressor responses to EAs injected into the RVLM of Dahl salt-sensitive rats are not enhanced by increased dietary salt intake, suggesting that salt-induced sensitization of RVLM neurons does not occur in these animals and so therefore does not contribute to the pathogenesis of hypertension in them. Unfortunately, that study did not attempt to control for the different baseline blood pressures, and therefore the interpretation of the data may not be straightforward.

Pawloski-Dahm and Gordon (22) previously argued that the enhanced pressor response elicited by injection of Glu into the RVLM of rats with elevated NaCl intakes was not the result of increased vascular responsiveness to sympathetic stimulation on the basis of their observations using 1-factor ANOVA with a post hoc Tukey test revealed that the low-salt group was statistically different from each of the other groups ($^*P < 0.05$), whereas control and high-salt diet groups were not statistically different. Regression analysis of data showed a significant correlation ($r = 0.69$, $P < 0.01$) between dietary salt intake and increase in MAP elicited by injection of nipeptic acid into NTS.

Fig. 4. Effect of dietary salt intake on change in MAP elicited by injection of nipeptic acid into nucleus of the solitary tract (NTS). Nipeptic acid (10 nmol) was injected bilaterally into NTS of groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% NaCl for previous 14 days ($n = 6$ or $7$ per group). Analysis of these results using 1-factor ANOVA with a post hoc Tukey test revealed that the low-salt group was statistically different from each of the other groups ($^*P < 0.05$), whereas control and high-salt diet groups were not statistically different. Regression analysis of data showed a significant correlation ($r = 0.69$, $P < 0.01$) between dietary salt intake and increase in MAP elicited by injection of nipeptic acid into NTS.

Fig. 5. Effect of dietary salt intake on depressor response elicited by injection of glutamate into NTS. Glutamate (50 pmol) was injected unilaterally into NTS of groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% NaCl for previous 14 days ($n = 6$–$8$ per group). These rats plus 6 additional rats in each dietary group received injections of 200 pmol of Glu into NTS. Each dose of glutamate injected into NTS elicited a significant decrease in MAP in all groups. With 50 pmol Glu, response in high-salt group was significantly greater than that in the other groups ($^*P < 0.05$); 200 pmol elicited a response that was similar in all groups. Glu injected into NTS also elicited a decrease in HR, although this response was not altered by dietary salt content (50 pmol: $210 \pm 2$, $215 \pm 7$, and $213 \pm 7$ beats/min in 0.01, 1, and 8% salt groups, respectively; 200 pmol: $221 \pm 3$, $225 \pm 5$, and $221 \pm 3$ beats/min).
electrical stimulation of the dorsolateral funiculus of the cervical spinal cord. In agreement with their data, the increase in MAP elicited by stimulation of vascular α-adrenergic receptors by intravenous injection of phenylephrine was not altered by increases in dietary salt intake. Similarly, Vollmer and colleagues (3, 15) noted that increased dietary salt intake did not increase the pressor response elicited by electrical stimulation of sympathetic outflow from the spinal cord in the pithed rat preparation. In addition, although in the present study blood volume was increased by 10.2 ± 0.3 ml/kg in rats with an elevated dietary salt intake, this had no effect on changes in MAP produced by intravenous injections of phenylephrine. Thus potentiation of RVLM-evoked pressor responses by increased dietary salt cannot be explained by an effect of salt on peripheral vascular reactivity. The potentiation of RVLM-evoked pressor responses by increased dietary salt also cannot be explained by changes in the baroreceptor reflex. Although decreased baroreceptor reflex buffering would result in a potentiation of responses evoked from the RVLM, increased dietary salt intake increases, rather than decreases, the gain of the baroreceptor reflex (11).

One difference between the present study and that of Pawloski-Dahm and Gordon (22) was the procedure used to force excess dietary salt consumption. Although Pawloski-Dahm and Gordon substituted 0.9% NaCl solution for the drinking water, we added NaCl to the food, with water available ad libitum. In the former method, blood Na⁺ concentration must be regulated solely by renal concentrating mechanisms, whereas when drinking water is always available the tonicity of body fluids can be adjusted in part by consuming more water. However, the similarity of results between the present study and those of Pawloski-Dahm and Gordon (22) suggests that it is the consumption of salt itself, rather than its exact mode of intake or elimination, that is important for augmented RVLM pressor responses.

Augmented pressor responses of rats with elevated dietary salt intake were not limited to those produced by activation of RVLM neurons via EAA receptors, they were also observed in response to injection of a cholinergic agonist (i.e., carbachol) and L-DOPA. Cholinergic agonists are known to increase the activity of RVLM sympathoexcitatory neurons (12) and to result in an increase in MAP when administered directly into the RVLM (8, 33). L-DOPA injected into the RVLM has also been shown to increase MAP (17, 35). The pressor action of L-DOPA does not involve its conversion to a catecholamine (17) and, although the receptor mechanisms by which DOPA injected into this brain region elicits a pressor response are not fully understood, the observation that this response is altered by changes in dietary salt intake provides further support for the hypothesis that in rats with a high dietary salt intake there is a general increase in the excitability of RVLM sympathoexcitatory neurons, regardless of which cell surface receptors are activated.

Complementary to the increased pressor responses elicited by stimulation of the RVLM in rats with high dietary salt intake, we examined the effect of ganglionic blockade on blood pressure in rats with different dietary salt intakes. Hexamethonium (30 mg/kg iv) was injected into groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% NaCl for previous 14 days (n = 5 or 6 per group). Baseline MAP, which was similar in all groups before ganglionic blockade (116 ± 8, 119 ± 5, and 105 ± 5 mmHg in 0.01, 1, and 8% dietary salt groups, respectively), fell to a lower level the higher the salt content of the diet (linear regression of dietary salt content and posthexamethonium MAP was highly significant, P < 0.01, r = 0.78). *P < 0.05 compared with 1.0% salt group. HR, which in these animals was slightly higher in rats on low-salt diet compared with 1% salt diet (P < 0.05; 412 ± 17, 365 ± 8, and 374 ± 9 beats/min in 0.01, 1, and 8% dietary salt groups, respectively) was not altered by hexamethonium.

### Fig. 6. Effect of ganglionic blockade on blood pressure in rats with different dietary salt intakes. Hexamethonium (30 mg/kg iv) was injected into groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% NaCl for previous 14 days (n = 5 or 6 per group). Baseline MAP, which was similar in all groups before ganglionic blockade (116 ± 8, 119 ± 5, and 105 ± 5 mmHg in 0.01, 1, and 8% dietary salt groups, respectively), fell to a lower level the higher the salt content of the diet (linear regression of dietary salt content and posthexamethonium MAP was highly significant, P < 0.01, r = 0.78). *P < 0.05 compared with 1.0% salt group. HR, which in these animals was slightly higher in rats on low-salt diet compared with 1% salt diet (P < 0.05; 412 ± 17, 365 ± 8, and 374 ± 9 beats/min in 0.01, 1, and 8% dietary salt groups, respectively) was not altered by hexamethonium.

### Fig. 7. Effect of dietary salt intake on phenylephrine-evoked increases in blood pressure. Bolus doses of phenylephrine were injected intravenously in groups of chloralose-anesthetized rats that had been fed diets containing 0.01, 1, or 8% NaCl for previous 14 days (n = 5 or 6 per group) and had been given hexamethonium to block autonomic reflexes. These are same rats presented in Fig. 6. Phenylephrine evoked a rapid and transient increase in MAP that was not significantly altered by dietary salt content.
elevated dietary NaCl intake, decreasing dietary salt intake (from ~4.5 to ~0.5 meq/day) diminished MAP responses elicited by Glu, carbachol, or DOPA injections into the RVLM. Indeed, for all of the centrally evoked pressor responses examined, there was a direct linear correlation between dietary salt content and magnitude of the evoked pressor response. The decreased sensitivity of RVLM sympathoexcitatory neurons to excitatory inputs in rats consuming a diet low in NaCl may contribute to the relatively decreased role of the sympathetic nervous system in the maintenance of baseline AP, as supported by the observation that ganglionic blockade did not decrease MAP as much in rats on a low-salt diet as it did in rats with higher salt intakes.

Alterations in dietary salt intake, in addition to its effects on pressor responses produced by injection of excitatory substances into the RVLM, influenced hypertensive responses observed when polysynaptic CNS pathways were activated by inhibition of NTS neurons with nipecotic acid as well as by activation of somato-sympathetic fibers. These observations indicate that changes in dietary salt consumption can alter central cardiovascular responses produced by the release of endogenous CNS transmitters in addition to direct pharmacological activation of RVLM neurons. The pressor response elicited by electrical stimulation of the sciatic nerve requires EAA-mediated neural transmission in the RVLM (16), and the alteration of this response by changes in dietary salt intake is consistent with this. Indeed, the extent to which changes in dietary salt intake altered the pressor response to sciatic nerve stimulation was identical to the effect of dietary salt content on the pressor response evoked by injection of Glu into the RVLM.

Changes in dietary salt intake also modify depressor responses elicited from the CNS. Injection of Glu into the NTS elicits a decrease in MAP similar to the response observed by stimulation of baroreceptor afferent fibers, which terminate in the NTS (28). Indeed, the exaggerated depressor response produced by injection of Glu into the NTS of rats with a high dietary salt intake is similar to the exaggerated depressor response to stimulation of baroreceptor afferent nerves noted by Pawloski-Dahm and Gordon (22) in rats with elevated dietary salt intake. This is consistent with the observation that high dietary salt intake increases the gain of baroreceptor-evoked changes in renal sympathetic nerve activity (11). Because baroreceptor-evoked decreases occur in MAP or sympathetic nerve activity are mediated via a pathway that results in inhibition of RVLM neurons, it is plausible that in rats with elevated dietary NaCl intake excitatory responses are enhanced in either the NTS or caudal ventrolateral medulla, resulting in enhanced inhibitory input to RVLM. Alternatively, alterations in dietary NaCl intake may change the responsiveness of RVLM neurons to both inhibitory and excitatory inputs.

In summary, the augmentation of centrally mediated pressor responses by a high-salt diet and their diminution by a low-salt diet strongly suggest that CNS mechanisms controlling arterial blood pressure respond to changes in dietary salt. However, it should be emphasized that all of the rats in this study were normotensive and baseline blood pressure was not different between the various groups. These observations indicate that dietary salt-induced changes in CNS sensitivity are not sufficient by themselves to alter the prevailing level of blood pressure. Instead, dietary salt-associated changes in central cardiovascular responsiveness may predispose toward a higher or lower AP by interacting with the many other mechanisms that regulate arterial blood pressure.

Perspectives: Salt and Hypertension

The role of dietary salt intake in the pathogenesis of hypertension has long been debated. The observation that elevated dietary NaCl intake causes enhanced pressor responses from the RVLM in normotensive rats raises the possibility that this mechanism may contribute to the hypertensogenic effects of NaCl. These observations also suggest that increased dietary Na+ intake does not directly cause an increase in blood pressure by itself but rather may potentiate the actions of other hypertensive stimuli.

These studies were supported by grants from the National Heart, Lung, and Blood Institute (HL-55687 to A. F. Sved and HL-53462 to F. J. Gordon) and the American Heart Association (Grant-in-Aid 95012950 to F. J. Gordon).

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Received 26 October 1998; accepted in final form 5 February 1999.

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