Hemodynamic Mechanisms of Adaptation to Chronic High Sodium Intake in Normal Humans

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SUMMARY  The long-term hemodynamic effects of a high dietary sodium intake were studied in 10 young normal subjects. After a 4-day diet of 10 mEq of sodium and 60 mEq of potassium per day the mean arterial blood pressure (MAP) was 82.3 ± 15.1 mm Hg, the cardiac index (CI) was 2.32 ± 0.69 liter/min/m², and total peripheral resistance (TPR) was 1778 ± 947 dyne sec cm⁻⁵. After 4 to 6 days of 200 mEq of sodium and 60 mEq of potassium per day, MAP was 84.3 ± 20.9 mm Hg, CI had risen to 2.53 ± 0.61 liter/min/m², and TPR fell to 1437 ± 328 dyne sec cm⁻⁵. After 6 months of unrestricted sodium intake, urinary sodium excretion (UNa) was 144.1 ± 51.9 mEq/24 hrs (p < 0.001), MAP remained at 83.1 ± 13.8 mm Hg, CI had risen to 3.11 ± 1.01 liter/min/m² (p < 0.05) and TPR was 1268 ± 444 dyne sec cm⁻⁵. After 12 months, UNa had risen to 171.5 ± 97.6 mEq/24 hrs (p < 0.005), while MAP remained at 82.4 ± 17.9 mm Hg, CI at 3.08 ± 1.16 liter/min/m² (p < 0.05), and TPR at 1282 ± 500 dyne/sec/cm⁻⁵. Thus, cardiac index rises significantly with sodium intake in normal subjects and remains at a higher level for as long as 12 months. Blood pressure does not rise because TPR falls proportionately. (Hypertension 5: 814-820, 1983)

KEY WORDS  •  sodium  •  hemodynamics  •  hypertension  •  echocardiography  •  diet

EPIDEMIOLOGIC studies have shown that the prevalence of hypertension rises with the level of a population's customary dietary sodium intake. However, in areas with an exceptionally high sodium intake, the majority of individuals remain free of hypertension. One model of essential hypertension proposes that certain individuals are born with a genetic predisposition which, when combined with a diet containing added sodium, leads to renal retention of sodium and water, and expansion of plasma and extracellular fluid volume with increased cardiac output. Chronic increase in cardiac output might stimulate autoregulation in the various tissues of the body leading to increased total peripheral resistance and increased blood pressure. However, normotensive individuals who do not restrict sodium must be able to circumvent this sequence of events. Our objectives were to identify individuals whose arterial blood pressure did not rise in response to sodium repletion over a 4-day period, to determine whether blood pressure varied from the levels observed during sodium repletion while they followed a high sodium intake for 1 year, and to study the hemodynamic mechanisms that might allow these individuals to adapt over the longer term to a diet containing approximately 200 mEq of sodium, without an elevation of blood pressure.

METHODS

The subjects were 43 normal volunteers (30 men, 13 women) whose average age was 27.9 years, ranging from 21 to 46 years; 38 were white and five were black. Twenty-one had a positive family history of hypertension. The protocol for this study was approved by the Patient Participation Committee of the University of Tennessee Center for the Health Sciences. All participants gave their informed consent. All subjects were admitted to a Clinical Research Center for interview, physical examination, and clinical laboratory studies that consisted of a complete blood count, urinalysis, serum creatinine, endogenous creatinine clearance, blood sugar and serum sodium, potassium, chloride, and bicarbonate.

To avoid the effects of hospitalization on blood pressure, all participants went about their normal activities throughout the study. They returned three times a day for meals and for measurement of blood pressure. The latter was measured in triplicate with an Arteriosonde (Roche Medical Electronics Division, Cranbury, New Jersey) after 5 minutes of rest in the supine position.

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followed by measurement after 2 minutes in the standing position. Weight was measured daily.

Twenty-four-hour urinary excretion of sodium, potassium, and creatinine was measured on the first day of the study while the patients followed their usual diet, and at the end of each 4-day study period. Hemodynamic studies were performed on the same days. Urinary sodium and potassium were measured with a flame photometer. After measurements had been made while the subjects were following their usual diet, the subjects were placed on a diet calculated to contain a daily intake of 10 mEq sodium and 60 mEq potassium, and all measurements were repeated on the morning of the fifth day. Urine sodium excretion at this time suggested that the actual daily sodium intake was approximately 20 mEq. Oral sodium intake was then increased to 200 mEq daily, potassium intake continued at 60 mEq daily, and measurements were again repeated on the morning of the 10th day.

The hemodynamic studies included echocardiography, from which stroke volume, cardiac output, and total peripheral resistance were calculated, and venous occlusion plethysmography, from which forearm blood flow and forearm vascular resistance were calculated.

Echocardiographic Studies

Echocardiographic images were obtained with a Toshiba SSH-10 phased-array, real-time and combined M-mode ultrasonograph (Toshiba America, Tustin, California). The transducer was placed on the chest wall and oriented to display the long axis view, which represents a sagittal cut through the heart from left ventricular apex to aortic root. An M-mode cursor was then positioned to intersect the maximum diameter of the left ventricle below the mitral valve leaflets and superior to the papillary muscles. This step assured that the area selected reflected midwall motion and that different dimensions could be identified on subsequent studies. The motion-mode ultrasound information was then recorded on a strip chart recorder (Honeywell Model 1856) at 25 and 50 mm/sec through three or four respiratory cycles with the patient breathing quietly. Auscultatory blood pressures were taken at the same time and recorded. The records were then measured at conventional measuring sites for left ventricular end-diastolic dimension and end-systolic dimensions.10 Systolic and diastolic volumes were calculated by the regression equation derived by Meyer et al.7: left ventricle = -19.1 + 14.6 Be + 0.62 Be1 with Be representing the echo-determined left ventricular dimension. Meyer and his coworkers7 correlated their echo data with biplane angiograms to obtain regression analysis for small to normal adult-sized left ventricles.

Stroke volume was determined by subtracting the systolic from diastolic volumes. Cardiac output was calculated as the product of simultaneous heart rate and stroke volume averaged over 10 seconds, and total peripheral resistance was calculated from the Frank formula using blood pressure measurements simultaneous with the echocardiographic studies:

\[
R = \frac{\text{mean arterial pressure (mm Hg)} \times 1330}{\text{cardiac output (ml/sec)}}
\]

Echocardiographic measurements were made by one of the authors (TER) without knowledge of the patient's status. The variability of the measurement of left ventricular dimensions by the same observer at different times was less than 2.0%. In separate experiments we have analyzed our method for reproducibility. Fifty-three subjects with normal ventricles were studied on two separate occasions after a 30-minute rest in the supine position. At the time of each study, triplicate measurements were made over a 20-minute period. The average variation of cardiac outputs calculated by this method was 11.6%. The accuracy and reproducibility of echographic measurement of left ventricular volume have been examined in several studies,8-13 and support the conclusion that echographic measurements are an acceptably accurate way to follow changes in volume with an intervention where the subjects have symmetrically contracting ventricles and serve as their own controls.14

Forearm Hemodynamic Studies

Plethysmography was used to measure forearm blood flow and vascular resistance.15,16 A mercury-filled, single-strand strain gauge, activated by a constant current, was connected to an impedance-matching circuit, a high-sensitivity, alternating current, carrier preamplifier, and an eight-channel Hewlett-Packard 7788A recorder. Patients were examined while supine after a 10-minute rest. An Arteriosonde was placed on the right arm to record arterial blood pressure at the time the plethysmographic tracing was made. The strain gauge-to-pan deflection ratio was determined by stretching the strain gauge 5 mm beyond its straightened length, measuring the deflection caused by the gauge on the recorder paper, and then dividing the strain-gauge stretch distance (5 mm) by the distance that the recorder pen was deflected on the graph paper. This calibration constant was measured for each patient. The strain gauge was wrapped around the forearm approximately 10 cm below the elbow, stretched 2% past its resting length, and secured with tape. A blood pressure cuff was placed on the upper left arm and rapidly inflated to 40 mm Hg to block venous return at the time of the tracing. Three resting tracings were made while simultaneously taking a blood pressure reading on the right arm. A 3- to 5-minute rest was allowed between tracings.

Small changes in forearm circumference cause changes in the length of the strain gauge, which result in linear changes in voltage across the ends of the strain gauge that are displayed on the recorder. The initial slope of plethysmographic record results from the veins filling with blood since venous return is blocked by the inflated cuff. The forearm blood flow was calculated from this first slope by the formula:
FBF (ml/min/100 g) = 
\[
\frac{2 \times (1\text{st slope}) \times (\text{calibration ratio}) \times (\text{chart speed mm/min})}{\text{Forearm circumference (Lo)}_{\text{mm}}}
\]

An automatic blood pressure reading was taken during each tracing, and mean arterial pressure was calculated. Forearm vascular resistance was calculated by the formula:

\[\text{FVR} = \frac{\text{MAP}}{\text{FBF}},\] expressed as mm Hg/ml/min/100 g.

On triplicate determination several minutes apart, MAP varied from the mean by 2.9%, forearm blood flow by 16.5%, and forearm vascular resistance by 16.6%.

Selection of Subjects for Long-Term Study
A decrease in MAP greater than 5% during the transition from the ad libitum diet to the salt-depleted state and an increase of 5% from the salt-depleted to the salt-repleted state were selected as measures of sodium sensitivity after examining the distribution of responses. Of 43 normal subjects, six were found to be sodium-sensitive and 37 to be sodium-resistant. The present study focuses on 10 consecutive subjects chosen from the 37 sodium-resistant normal subjects who agreed to participate in a long-term study of dietary sodium intake.

The average age of these subjects was 30 years, with a range of 20–46 years; five were men, five were women, and four had a positive family history of hypertension. They all received instructions from our research dieticians and agreed to follow a daily diet containing approximately 200 mEq of sodium and 60 mEq of potassium. They entered the study at different times during the year.

Blood pressure was monitored at monthly intervals so that any potentially harmful increase in blood pressure could be detected. At 6 and 12 months, body weight, heart rate, blood pressure, echocardiographic and plethysmographic studies, and 24-hour urines for measurement of sodium, potassium, and creatinine excretion were remeasured. Echocardiographic studies of sufficient quality for measurement could not be obtained at either 6 or 12 months in three patients.

During the same period, seven women with mild mitral valve prolapse were followed with echocardiographic examinations repeated at intervals of 12 months while they followed an ad libitum diet. These subjects ranged in age from 22 to 49 years (average age, 32 years).

Data Analysis
All data were tabulated in original and translated forms and entered on punch cards. Data were tested for significance by analysis of variance, taking into account repeated measures using a PDP-11/70 computer (Digital Equipment Corporation, Maynard, Massachusetts). A Newman-Keuls’ a posteriori test was used to determine where differences lay when significant differences were found during analysis of variance.17

Results

Urinary sodium excretion averaged 120 mEq daily on an ad libitum diet. In the 10 sodium-resistant normal subjects, sodium excretion fell to 19 mEq per day during sodium depletion and rose to 84.4 mEq a day during initial sodium repletion. With chronic adherence to a high salt diet, sodium excretion rose to 144 mEq daily at 6 months and to 171 mEq daily at 12 months. Urinary potassium excretion did not vary significantly during this period. Similarly, there was no statistically significant increase in weight nor in systolic BP, diastolic BP, or MAP. There were no measurable changes in left ventricular septal, posterior wall thickness, or fractional shortening. However, cardiac index (CI) fell during sodium depletion and, with continued adherence to a high sodium intake, rose significantly to levels higher than those observed during either the period of sodium depletion or the ad libitum period. Total peripheral resistance (TPR) tended to rise during sodium depletion and to fall during sodium

| Table 1. Long-Term Hemodynamic Effects of Sodium Intake in Seven Humans |
|------------------------|-----------------------------|-----------------------------|-----------------------------|
|                        | Ad lib diet                 | Sodium depletion 4 days     | Sodium repletion 6 mo        |
|                        |                             |                             |                             |
| Urine sodium (mEq/24 hr)| 120.3 ± 8.5                 | 19.2 ± 12.2*                | 84.4 ± 35.7                 |
| Urine potassium (mEq/24 hr)| 50.7 ± 14.6             | 39.5 ± 14.0                 | 38.9 ± 16.9                 |
| Weight (kg)            | 70.3 ± 14.9                 | 67.7 ± 14.2†               | 69.7 ± 13.9                 |
| MAP (mm Hg)            | 87.3 ± 15.1                 | 82.3 ± 15.1                 | 84.3 ± 20.9                 |
| CI (liter/min/m²)      | 2.63 ± 0.74                 | 2.32 ± 0.69                 | 2.53 ± 0.61                 |
| TPR (dyne/sec/cm⁻⁵)    | 1570 ± 666                  | 1778 ± 947                  | 1437 ± 328                  |
|                       | 12 mo                       |                             |                             |
|                       |                             |                             | 171.5 ± 97.6 (SD)*          |
|                       |                             |                             | 46.2 ± 26.5                 |
| MAP = mean arterial blood pressure, CI = cardiac index, TPR = total peripheral resistance. |
| *p = < 0.025.         |                             |                             | *p = < 0.05.                |
| †p = < 0.05.          |                             |                             |                             |
repletion, but the changes were not statistically significant (table 1). The initial CI of the subjects with mild mitral valve prolapse was 3.94 ± 0.69 liter/min/m². Twelve months later, CI was approximately the same at 3.93 ± 1.5 liter/min/m².

The CI can vary because of changes in either heart rate, stroke volume, or both. During this trial, heart rate did not change significantly. The main factor responsible for the change in CI was a change in stroke volume, which fell significantly during sodium depletion and rose significantly with sodium repletion (table 2). These changes were due primarily to significant changes in left ventricular end-diastolic volume during sodium depletion and repletion, as left ventricular end-systolic volume remained relatively constant during the trial. Thus, the hemodynamic changes appear to be due to increased diastolic filling of the heart during a high salt diet. When the data were replotted to examine the relationship between urinary sodium excretion and CI, we found an upward trend between daily intakes of 20 and 140 mEq of sodium, with an apparent plateau at levels above that point (fig. 1). This relationship was not linear (R = 0.364, p > 0.1).

In previous studies, we found that sodium-sensitive individuals responded to sodium depletion with a significant increase in forearm vascular resistance. In contrast, sodium-resistant individuals showed a lesser change. Similarly, in the present study, we found no significant change in forearm vascular resistance when sodium-resistant subjects followed a high sodium intake for 12 months (table 3).

### Table 2. Long-Term Effects of Sodium Intake on Cardiac Dimensions in Seven Humans

<table>
<thead>
<tr>
<th>Cardiac dimension</th>
<th>Ad lib diet</th>
<th>Sodium depletion 4 days</th>
<th>Sodium repletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (bpm)</td>
<td>67.6 ± 10.1</td>
<td>67.9 ± 12.7</td>
<td>73.4 ± 9.8</td>
</tr>
<tr>
<td>Stroke volume (ml/beat)</td>
<td>70.8 ± 19.3</td>
<td>61.2 ± 14.3†</td>
<td>73.2 ± 15.6</td>
</tr>
<tr>
<td>LV end diastolic volume (ml)</td>
<td>105.9 ± 34.1</td>
<td>96.5 ± 26.7</td>
<td>105.2 ± 35.9</td>
</tr>
<tr>
<td>LV end systolic volume (ml)</td>
<td>41.4 ± 12.7</td>
<td>41.6 ± 17.5</td>
<td>39.6 ± 11.1</td>
</tr>
<tr>
<td>LV end diastolic dimension (mm)</td>
<td>46.4 ± 3.9</td>
<td>45.1 ± 2.5†</td>
<td>46.7 ± 4.5</td>
</tr>
<tr>
<td>LV end systolic dimension (mm)</td>
<td>29.6 ± 4.6</td>
<td>30.0 ± 4.8</td>
<td>29.7 ± 3.5</td>
</tr>
</tbody>
</table>

*p = 0.00008.
†p = < 0.02.
‡p = < 0.05.

**Figure 1.** Relation of cardiac index to daily urinary excretion of sodium. Data are expressed as means ± SEM. Cardiac index was significantly higher when daily urinary sodium excretion was 140 mEq per day or more than at other times. p < 0.025.

### Table 3. Long-Term Forearm Hemodynamic Effects of Sodium Intake on 10 Humans

<table>
<thead>
<tr>
<th>Hemodynamic measurement</th>
<th>Ad lib diet</th>
<th>Sodium depletion 4 days</th>
<th>Sodium repletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm blood flow (ml/min/100 g)</td>
<td>7.36 ± 4.7</td>
<td>8.0 ± 6.3</td>
<td>8.56 ± 5.7</td>
</tr>
<tr>
<td>Resistance (mm Hg/ml/min/100 g)</td>
<td>16.8 ± 8.9</td>
<td>15.5 ± 8.2</td>
<td>14.5 ± 8.2</td>
</tr>
</tbody>
</table>

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Discussion

When common laboratory rats receive a high sodium diet, a minority develop increased blood pressure. With selective in-breeding, strains of rats can be developed that invariably develop hypertension when fed sodium. Cross-transplantation studies suggest that this genetic predisposition to salt sensitivity is linked to the kidney.

Epidemiologic studies have shown that the prevalence of hypertension in human populations rises with habitual sodium intake. The highest sodium intake is found among inhabitants of the northern Japanese island, where a daily intake of 30 g is common. Nonetheless, approximately 60% of the individuals chronically exposed to this unusually high level of dietary sodium continue to have diastolic blood pressures less than 95 mm Hg. Thus, like the rat, a majority of human beings are able to tolerate a high sodium diet without developing hypertension.

The mechanisms by which the majority of human beings adapt to a chronically high sodium diet without developing hypertension are not known but are undoubtedly complex, given the multiplicity of hemodynamic, hormonal, nervous, and metabolic factors that are involved in the normal regulation of blood pressure. The present study focuses on the hemodynamic changes that accompany long-term increases in dietary sodium among normotensive individuals who did not appear to be sodium-sensitive on short-term testing. In previous studies, we have found that about 85% of normotensive individuals could change from a daily intake of 10 mEq sodium to 200 mEq sodium per day without a significant change in blood pressure over a 4-day period, even though weight and CI increased significantly. An increase in blood pressure did not take place because a proportionate fall in TPR accompanied the increase in cardiac output.

We thought it important to determine whether this increase in cardiac output persisted with time. In the present study, 10 subjects were followed who agreed to continue to adhere to a high sodium intake for at least 1 year. During this time, measurements were made while average sodium intake varied from 19.2 to 171.5 mEq per day, with no significant change in blood pressure. Although MAP values were identical at the two extremes of sodium intake, the CI rose significantly by 34.1% with increasing sodium intake. In contrast, the CI remained virtually unchanged in patients with mild mitral valve prolapse who followed an ad libitum diet. Although the changes in TPR of the subjects following a high sodium diet did not reach statistical significance, blood pressure did not rise because of a downward trend in TPR of 27.9%. Thus, in normal humans, maintenance of pressure took precedence over maintenance of flow in the range of CI studied.

In the rat with one-kidney renovascular hypertension and in the sodium-loaded dog with reduced renal mass, the sequence of development of hypertension begins with an expansion of extracellular volume, followed by an increase in cardiac output, which in turn triggers total body autoregulation. The latter leads to an increased total peripheral resistance, elevated blood pressure, pressure diuresis, and a return of cardiac output to normal while hypertension persists. Total body autoregulation can also be demonstrated by raising cardiac output with intravenous volume expansion. However, demonstration of acute autoregulation has involved doubling the cardiac output. In the present study, cardiac output rose far less, 33%, which does not appear to trigger measurable total body autoregulation in normal humans in 1 year of observation. Our data do not exclude the possibility that regional vascular beds might autoregulate. It is known that outer cortical renal blood flow increases with sodium intake while arterial pressure remains unchanged. Thus, renal vascular resistance falls, which might contribute to the downward trend in TPR with continued high sodium intake, and this we observed. All vascular beds did not vasodilate, as we noted no consistent changes in forearm vascular resistance. It is possible that significant degrees of total body autoregulation do not take place in normal subjects until the CI is increased beyond 33%, or that adaptation to a higher CI in humans involves increased arteriolo-venular shunting.

The increase in CI that we observed appeared to be due to an increase in preload, because end-diastolic volume and stroke volume rose significantly while end-systolic volume and heart rate did not. This observation together with the increased CI indicate an increase in venous return, which may be due to an increase in intravascular and extracellular volume, although we did not measure these factors. A decrease in venous compliance during sodium repletion provides another possible explanation for an increased venous return, as suggested by the observations of Takeshita et al. We did not measure the activity of the sympathetic nervous system, which could provide an alternative explanation for the increased output. However, the lack of a significant increase in heart rate in our study does not suggest increased sympathetic activity. Similarly, Luft et al. observed a fall in plasma norepinephrine during sodium loading.

There have been relatively few studies that have examined the hemodynamic effects of acute sodium loading or high sodium intake in normal human subjects. Kirkendall et al. observed that a daily intake of 410 mEq of sodium for 1 month resulted in an increase in forearm blood flow with only a 1 mm Hg increase in mean arterial pressure; therefore, forearm vascular resistance fell. Luft et al. studied normal subjects on diets ranging from 10 to 1500 mEq sodium per day for 3-day intervals. They found that blood pressure rose significantly, but only 7.3 mm Hg at a daily intake of 800 mEq, due to an increase in cardiac output.

In subjects with labile hypertension, Julius et al. noted that interventions that altered cardiac output, such as dextran infusion, posture, or exercise, could bring out a disproportion between output and resistance, although the responses varied among individuals. Mark et al. noted an increase in forearm vascu-
lar resistance when borderline hypertensive subjects followed a 410 mEq sodium diet daily for 10 days. In subjects with established hypertension, Kawasaki et al. demonstrated that a daily intake of 249 mEq sodium over a period of 1 week caused an increase in MAP of more than 10% in nine of 19 patients.

Onesti et al. studied the hemodynamic effects of dietary sodium in patients with end-stage renal disease and bilateral nephrectomy. Although previously normotensive patients showed no significant changes in MAP or TPR when sodium intake was liberalized, previously hypertensive subjects showed parallel increases in MAP and TPR, which could be reversed by sodium depletion. Kim et al. showed that certain sodium-loaded anephric subjects can develop a high cardiac output without evidence of autoregulation.

A large body of data suggest that sodium-dependent forms of hypertension are related to the release of a ouabain-like natriuretic factor from the central nervous system. This factor inhibits Na⁺, K⁺-ATPase, thus reducing energy-requiring transport of sodium and potassium in cardiac and vascular smooth muscle. In turn, this results in vasoconstriction, increased cardiac contractility, and elevation of blood pressure. Although CI increased with sodium loading in our study, we attribute this to an increase in preload, as we were able to measure a significant change in end-diastolic dimensions but not in fractional shortening.

Our long-term observations are consistent with other short-term studies in normal subjects and in anephric subjects, as well as with our short-term studies, all of which have shown that normal subjects respond to an increase in dietary sodium with an increase in flow, which is accompanied by a decrease in resistance. In summary, we have found that in approximately 85% of normal subjects blood pressure was not altered significantly in response to short-term dietary sodium depletion and repletion. An additional 12 months of relatively high sodium intake was not accompanied by a rise in blood pressure in a group of 10 salt-resistant individuals. Left ventricular size and CI fell during sodium depletion, increased during sodium repletion, and remained higher during the entire 12 months of high sodium intake. Blood pressure did not rise because of a downward trend of TPR amounting to 28%, which was in approximate proportion to the rise in CI of 33%. No evidence of total body autoregulation in response to a higher cardiac output was noted during the 12 months of observation. Our data do not exclude the possibility that a still higher CI would stimulate autoregulation.

Conclusions

We conclude that normal individuals, possibly those free of a genetic predisposition to develop hypertension in response to dietary sodium, adapt to a chronically high sodium intake, at least in the range studied, by lowering TPR to accommodate a higher CI. Thus, in normal subjects, clinically significant increases in MAP and TPR do not appear to take place during a 12-month period in which sodium intake is varied about 10-fold, from 19 to 170 mEq/day.

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Hemodynamic mechanisms of adaptation to chronic high sodium intake in normal humans.
J M Sullivan and T E Ratts

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