Estimating Dietary Sodium Intake in Individuals Receiving a Randomly Fluctuating Intake

FRIEDRICH C. LUFT, M.D., NAOMI S. FINEBERG, PH.D., AND REBECCA S. SLOAN, R.N.

SUMMARY Previous investigations examining techniques to estimate sodium intake in free-living persons failed to consider a varying intake or were not conducted under circumstances in which the intake was actually known. To examine the utility of 24-hour and nocturnal urine collections as estimation of sodium intake under such conditions, we studied 43 white and black men and women ingesting a known sodium intake for 10 days that was randomly varied daily, with a mean intake of 150 mEq/day ± 2 σd (range, 50 to 250 mEq/day). The mean 24-hour sodium excretion (UNV) per day was 141 mEq/day while the mean sodium intake was 151 mEq/day. On a randomly selected day, both nocturnal and 24-hour UNV estimated that day's sodium intake reasonably well (r = 0.55). A stepwise regression showed that including consideration of age and blood pressure improved the correlation (r = 0.70). However, to estimate mean sodium intake accurately for the entire 10 days, the average of several 24-hour collections was required. Nine collections were optimal (r = 0.75). Nocturnal specimens were not helpful; the average of all 10 collections correlated weakly (r = 0.30) with sodium intake. These data suggest that to estimate mean sodium intake accurately in free-living persons, only 24-hour collections are useful, although nocturnal collections are helpful in evaluating compliance with low sodium intake.

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KEY WORDS • sodium • salt • salt restriction • sleep • nocturnal sodium • diurnal rhythms • nutrition

A high sodium intake has been implicated for centuries in the development of hypertension. Numerous studies in humans and experimental animals have suggested a causal relationship, and the efficacy of sodium restriction in the treatment of essential hypertension is well recognized. A major impediment in assessing the relationship between sodium intake and hypertension, or the effects of dietary sodium restriction, however, has been the accurate estimation of dietary sodium intake. Several studies suggest nocturnal urine collections, and we recently examined the utility of overnight urine collections in subjects ingesting a known, but fixed, sodium intake. Although our results suggested that nocturnal urine collections are helpful, particularly in demonstrating compliance with a low sodium intake, our protocol did not take into consideration the behavior of free-living individuals. Normally humans do not ingest a fixed sodium intake, but rather vary their diet according to habit, desire, and food availability. The present study was designed to examine the value of nocturnal urine collections in individuals who randomly and regularly alter their sodium intake.

Methods

After due approval and informed consent, 22 white and 21 black men and women ranging in age from 19 to 54 years participated in the study. The subjects were either students at Indiana University or employees of the Indiana University Medical Center, selected for their ability to comprehend instructions and for their compliance in previous studies. They ate all meals in the Clinical Research Center, but were otherwise free to go as usual. They were given a constant daily diet containing 10 mEq sodium, 80 mEq potassium, 80 g protein, 80 g fat, 370 g carbohydrate, 400 mg calcium, and 1200 mg phosphorus. To this diet, 140 mEq of sodium was added in the form of sodium chloride, to raise the sodium intake to 150 mEq/day. The subjects ate and drank only those foods and beverages that they received from the Clinical Research Center. Plate waste was minimized by the use of rubber spatulas and bread. They ate an evening snack between 2000 and 2200 hours. The subjects ingested this diet for 5 days, and then for 10 days had the sodium chloride content of their diet randomly varied. A computer program generated 10 sodium intake levels for each subject; the levels were drawn from normal random numbers, with a mean of 150 mEq/day and a standard deviation of 50 mEq/day. Each subject received a known amount of deionized water each day.

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The subjects were instructed to collect all urine in two daily fractions: 0600 to 2200 hours and 2200 to 0600 hours, respectively. The subjects were weighed every morning after voiding. Pulse and blood pressure in the sitting position were obtained before each meal by means of the standard indirect auscultatory technique (Baum, Inc., New York, New York). The same observers were responsible for these measurements throughout the study. Sodium and potassium were measured by flame photometry (Corning Scientific Instruments, Medfield, Massachusetts). Creatinine was measured by an automated technique (Beckman Instruments, Fullerton, California). The data were analyzed by analysis of variance (repeated measures when indicated) and t tests, as appropriate. Relationships were tested by linear regression and step-wise multiple regression analysis. The 95% limits of probability were accepted as significant. Data are expressed as mean ± SEM.

Results

Table 1 shows the levels of urinary sodium, potassium, and creatinine excretion, as well as blood pressure measurements obtained on the 5th day of the fixed 150 mEq/day sodium intake. The subject groups did not differ with respect to 24-hour sodium or potassium excretion. Creatinine excretion was greater in men than women, and in younger than older subjects, probably reflecting differences in muscle mass. Older subjects excreted slightly more sodium at night than younger subjects. Men had slightly higher systolic blood pressures than women.

Table 2 shows the mean sodium intakes, as well as the mean 24-hour and nocturnal urinary excretions of sodium, potassium, and creatinine for all 10 days of the randomly fluctuating sodium intake period. For all groups, intake of sodium approached 150 mEq/day, and the mean excretion ranged from 135 to 142 mEq/day, demonstrating compliance with the regimens. When the mean sodium intakes and excretions were determined over the entire 10 days, and the differences obtained, intake exceeded excretion by 12.2 mEq/day + 13.3 SEM; ± 2.2 SEM.

There was no difference between groups in 24-hour or nocturnal sodium excretion, or 24-hour potassium excretion. Whites had a slightly higher nocturnal potassium excretion than blacks, a phenomenon also noted in younger, compared to older, subjects. Blacks excreted slightly more creatinine than whites, reflecting modest differences in muscle mass.

Table 3 shows correlations between either 24-hour or nocturnal sodium excretion and mean sodium intake during the 10 days of fluctuating intake. A single day's 24-hour urinary sodium excretion was not correlated with mean sodium intake. The average 24-hour urinary sodium excretion for any 2 days was weakly (p < 0.01) correlated with mean sodium intake. Thereafter, increasing the number of days considered in the regression correspondingly increased the correlation. Thus, any 9-day averaged 24-hour sodium excretion correlated highly with mean sodium intake (r = 0.75, p < 0.001). Adding the 10th day failed to improve the correlation. Step-wise multiple regression analysis showed that the added consideration of diastolic blood pressure improved the relationship (r = 0.79, p < 0.001) according to the following expression: mean salt intake = 0.72 x average of 9 days 24-hour U_n NaV + 0.59 x diastolic blood pressure + 97.38.

Nocturnal U_n NaV correlated poorly with mean sodium intake. The average for the 9-day nocturnal U_n NaV

<table>
<thead>
<tr>
<th>Variable</th>
<th>All subjects</th>
<th>White</th>
<th>Black</th>
<th>ANOVA</th>
<th>Age (yrs)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>Men</td>
<td>Women</td>
<td>&lt; 40</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>24-hr U_n NaV (mEq)</td>
<td>135 ± 4</td>
<td>133 ± 10</td>
<td>139 ± 8</td>
<td>130 ± 6</td>
<td>140 ± 12</td>
<td>NS</td>
</tr>
<tr>
<td>Nocturnal U_n NaV (mEq)</td>
<td>30 ± 2</td>
<td>29 ± 6</td>
<td>35 ± 5</td>
<td>26 ± 2</td>
<td>33 ± 7</td>
<td>NS</td>
</tr>
<tr>
<td>24-hr U_K (mEq)</td>
<td>60 ± 2</td>
<td>64 ± 2</td>
<td>60 ± 7</td>
<td>57 ± 3</td>
<td>60 ± 7</td>
<td>NS</td>
</tr>
<tr>
<td>Nocturnal U_K (mEq)</td>
<td>11 ± 1</td>
<td>10 ± 1</td>
<td>9 ± 1</td>
<td>11 ± 1</td>
<td>12 ± 2</td>
<td>0.001*</td>
</tr>
<tr>
<td>24-hr U_Cr (mg)</td>
<td>1600 ± 80</td>
<td>178 ± 6</td>
<td>111 ± 8</td>
<td>202 ± 11</td>
<td>125 ± 11</td>
<td>0.001*</td>
</tr>
<tr>
<td>Nocturnal U_Cr (mg)</td>
<td>480 ± 20</td>
<td>53 ± 3</td>
<td>32 ± 3</td>
<td>62 ± 4</td>
<td>35 ± 2</td>
<td>0.001*</td>
</tr>
<tr>
<td>Systolic BP (mm Hg)</td>
<td>120 ± 1</td>
<td>122 ± 2</td>
<td>115 ± 3</td>
<td>124 ± 2</td>
<td>115 ± 3</td>
<td>0.001*</td>
</tr>
<tr>
<td>Diastolic BP (mm Hg)</td>
<td>80 ± 1</td>
<td>82 ± 2</td>
<td>77 ± 2</td>
<td>81 ± 2</td>
<td>80 ± 2</td>
<td>NS</td>
</tr>
</tbody>
</table>

*Men vs women (p < 0.001). ANOVA = analysis of variance
was barely significant ($p = 0.043$). The relationship failed to improve in an incremental fashion as did the 24-hour collections. The average of two nocturnal collections, or nine nocturnal collections, correlated to an equal degree with mean sodium intake.

When randomly selecting a single day's 24-hour and nocturnal urinary sodium excretion, relationships were identified between sodium excretion and that day's sodium intake. On Day 5 of the randomly fluctuating sodium intake, step-wise multiple regression analysis revealed the following relationships in their order of entry: sodium intake vs nocturnal $U_{NaV}$ ($r = 0.55$); + diastolic blood pressure ($r = 0.65$); + age ($r = 0.70$); + 24-hour $U_{NaV}$ ($r = 0.74$). Substituting the relative positions of 24-hour and nocturnal $U_{NaV}$ did not significantly influence the relationships. Either variable served equally well.

**Discussion**

Under normal circumstances, the kidneys serve as the sole route for sodium excretion, making rapid adjustments to changes in dietary sodium intake to maintain homeostasis.$^{12}$ Hollenberg,$^{21}$ in a review of renal sodium cybernetics, stated that the setpoint for that regulatory system is situated at a very low sodium intake, less than 10 mEq/day. Normally, sodium intake is not constant but continuously changing, so that sodium balance is never achieved. Acculturated humans ingest sodium at a level far above the setpoint,$^{24}$ and, as a result, the kidneys are usually faced with the task of continuously excreting sodium in relatively large amounts. When daily sodium intake is maintained constant, 24-hour urinary sodium excretion approaches sodium intake after several days. The half-life required for the establishment of homeostasis is about 24 hours in adults.$^{22,25,26}$

When daily sodium intake is constant, 24-hour urine collections reflect sodium intake accurately over a very wide range of intakes.$^{27}$ Since nocturnal sodium excretion is correlated with 24-hour sodium excretion, nocturnal collections have been advocated.$^{18,19}$ Liu et al.$^{17}$ pointed out the inappropriateness of correlating the overnight sodium excretion with the corresponding 24-hour value, since the estimated correlation is inflated by the dependency of the intrindividual variation of the overnight and corresponding 24-hour measurements. Our data raise an additional issue. Dietary intake is normally altered on a daily basis, reflecting habit, food availability, and personal preferences. It is the mean dietary sodium intake rather than any individual day's intake that is important in establishing the role of sodium intake in disease, as well as in assessing the effects of dietary intervention.

The degree to which free-living individuals vary their day-to-day sodium intake is not known. On the basis of the mean 24-hour urinary sodium excretion, including range and frequency distribution, of the 379 normal white and black, middle-class Indiana residents in our study,$^{28}$ we selected a mean sodium intake of 150 mEq/day and a random fluctuation about that mean within 2 SD (50 mEq/day). These values are

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**Table 2. Urinary Values Averaged over the 10 Days of Randomly Fluctuating Sodium Intake (Mean ± SEM)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>All subjects</th>
<th>White</th>
<th>Black</th>
<th>Age (yrs)</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium intake (mEq)</td>
<td>151 ± 3</td>
<td>145 ± 4</td>
<td>154 ± 6</td>
<td>&lt; 40</td>
<td>NS</td>
</tr>
<tr>
<td>24-hr $U_{NaV}$ (mEq)</td>
<td>139 ± 3</td>
<td>143 ± 4</td>
<td>136 ± 5</td>
<td>&gt; 40</td>
<td>NS</td>
</tr>
<tr>
<td>Nocturnal $U_{NaV}$ (mEq)</td>
<td>28 ± 1</td>
<td>27 ± 1</td>
<td>33 ± 5</td>
<td>&lt; 0.05</td>
<td>NS</td>
</tr>
<tr>
<td>24-hr $U_{kV}$ (mg)</td>
<td>62 ± 1</td>
<td>63 ± 3</td>
<td>64 ± 5</td>
<td>&lt; 0.05</td>
<td>NS</td>
</tr>
<tr>
<td>Nocturnal $U_{kV}$ (mEq)</td>
<td>11 ± 0.4</td>
<td>10 ± 0.3</td>
<td>9 ± 0.5</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>24-hr $U_{cV}$ (mg)</td>
<td>1621 ± 83</td>
<td>1829 ± 61</td>
<td>1007 ± 75</td>
<td>0.001*</td>
<td></td>
</tr>
<tr>
<td>Nocturnal $U_{cV}$ (mg)</td>
<td>471 ± 21</td>
<td>542 ± 20</td>
<td>287 ± 23</td>
<td>0.001*</td>
<td></td>
</tr>
</tbody>
</table>

*Men vs women ($p < 0.001$).
*Black vs white ($p < 0.05$).

**Table 3. Correlations with Mean Sodium Intake over 10 Days of Randomly Fluctuating Intake**

<table>
<thead>
<tr>
<th>No. of days</th>
<th>24-hr $U_{NaV}$</th>
<th>Nocturnal $U_{NaV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>NS</td>
</tr>
<tr>
<td>2</td>
<td>0.33</td>
<td>0.014</td>
</tr>
<tr>
<td>3</td>
<td>0.29</td>
<td>0.031</td>
</tr>
<tr>
<td>4</td>
<td>0.37</td>
<td>0.008</td>
</tr>
<tr>
<td>5</td>
<td>0.46</td>
<td>0.001</td>
</tr>
<tr>
<td>6</td>
<td>0.52</td>
<td>0.001</td>
</tr>
<tr>
<td>7</td>
<td>0.62</td>
<td>0.001</td>
</tr>
<tr>
<td>8</td>
<td>0.71</td>
<td>0.001</td>
</tr>
<tr>
<td>9</td>
<td>0.75</td>
<td>0.001</td>
</tr>
<tr>
<td>10</td>
<td>0.75</td>
<td>0.001</td>
</tr>
</tbody>
</table>
consistent with those of Liu et al.,29 who found a mean sodium excretion of 176 ± 58 mEq in 167 businessmen. Our data show that a single 24-hour measurement of urinary sodium excretion was of no value in assessing mean sodium intake accurately; instead, nine 24-hour collections were necessary. Interestingly, Liu et al.29 estimated that seven to 14 24-hour urine collections would be necessary. It is disappointing, but not altogether surprising, that our data indicate that nocturnal urine collections are not helpful in estimating mean sodium intake, since the relationship between nocturnal and 24-hour collections is no longer linear due to fluctuating intake. (There is a linear relationship when sodium intake is maintained constant.23) Thus, increasing the number of nocturnal specimens failed to improve the correlation. On the other hand, 24-hour and nocturnal collections were valuable in estimating the sodium intake for that day. Unfortunately, a single day’s intake provides little information in assessing mean sodium intake.

The correlations in our study were improved when age and diastolic blood pressure were considered in the relationships. Both age and blood pressure may influence the relationship between nocturnal and 24-hour renal sodium excretion. We have previously shown that older individuals, first-degree relatives of hypertensives, and black Americans excrete an intravenous 300 mEq sodium challenge more slowly than control subjects, and excrete correspondingly more of the sodium load at night.28,30 In the present investigation we could find no influence of race or gender on the relationships.

These results underscore the difficulty in assessing dietary sodium intake and serve to explain, at least in part, the poor correlation between dietary recall and urinary sodium excretion.31 Our data apply only to populations that have a mean sodium intake of 150 ± 50 mEq/day, with a random fluctuation within 2 s. It is possible that populations that vary their intake across a smaller range, or have a considerably lower intake, show better correlations between single, or substantially fewer, 24-hour urine collections. In summary, nocturnal urine collections do not appear promising in the estimation of mean sodium intake. They are clearly valuable, however, in assessing compliance with low-sodium regimens.30 Moreover, it is possible that nocturnal specimens may permit the categorization of individuals with respect to sodium intake, when techniques such as cluster analysis are applied. Further studies on populations randomly varying their sodium intake about different mean intakes will be necessary to examine the issue.

References


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