Response of Aldosterone and Blood Pressure to Angiotensin II Infusion in Anephric Man

Effect of Sodium Deprivation


SUMMARY: Angiotensin II, infused intravenously, increased plasma aldosterone concentration in two of six anephric subjects taking their usual dietary quantities of sodium. After 3 days of dietary sodium restriction and weight-reducing hemodialysis, the aldosterone response to infused angiotensin II in the two previously reactive subjects was enhanced, while the four previously unreactive subjects also showed a rise in plasma aldosterone. Before and after sodium depletion the anephric subjects were less responsive than normal subjects. Even when sodium-depleted, the anephrics showed no further rise in plasma aldosterone when arterial plasma angiotensin II was increased by infusion to concentrations > 50-100 pg/ml, in contrast to sodium-depleted normals who show progressive aldosterone responses with plasma angiotensin II concentrations up to at least 370 pg/ml. Before the infusion of angiotensin II, arterial plasma renin, angiotensin II, and aldosterone were detectable in the anephrics, but were unchanged by dietary sodium restriction or weight-reducing hemodialysis. Sodium depletion caused significant falls in weight, plasma sodium, and blood pressure, but no changes in plasma potassium or cortisol. Increases in blood pressure in relation to increments of arterial plasma angiotensin II were unaffected by sodium depletion, as might be expected in the absence of a rise in endogenous angiotensin II.

Although previously disputed, several studies recently have shown that in man the adrenal cortex is sensitized by sodium depletion in that the dose-response curve relating plasma aldosterone concentration in two of six anephric subjects taking their usual dietary quantities of sodium. After 3 days of dietary sodium restriction and weight-reducing hemodialysis, the aldosterone response to infused angiotensin II in the two previously reactive subjects was enhanced, while the four previously unreactive subjects also showed a rise in plasma aldosterone. Before and after sodium depletion the anephric subjects were less responsive than normal subjects. Even when sodium-depleted, the anephrics showed no further rise in plasma aldosterone when arterial plasma angiotensin II was increased by infusion to concentrations > 50-100 pg/ml, in contrast to sodium-depleted normals who show progressive aldosterone responses with plasma angiotensin II concentrations up to at least 370 pg/ml. Before the infusion of angiotensin II, arterial plasma renin, angiotensin II, and aldosterone were detectable in the anephrics, but were unchanged by dietary sodium restriction or weight-reducing hemodialysis. Sodium depletion caused significant falls in weight, plasma sodium, and blood pressure, but no changes in plasma potassium or cortisol. Increases in blood pressure in relation to increments of arterial plasma angiotensin II were unaffected by sodium depletion, as might be expected in the absence of a rise in endogenous angiotensin II.
Methods

All experimental procedures were approved by the Ethical Supervisory Committee of the Western Infirmary, Glasgow. Informed consent was obtained from the six subjects, none of whom suffered adverse effects or complained of unusual symptoms during the study. Details of the subjects' status are given in Table 1. All were taking a slightly reduced quantity of dietary sodium, as is customary with regular dialysis treatment. In all instances their usual dietary intake of sodium and potassium was continued after admission to the ward for the 1st day of the experiment. One subject (no. 2, Table 1) was taking an oral contraceptive containing 0.05 mg estrogen/3 mg progestagen (Controlyl, Schering) throughout the experimental study. None of the other subjects was receiving medication apart from supplementary oral vitamin and iron preparations.

On day 1 the first hemodialysis was performed with a Cordis-Dow Mark 4 hollow-fiber artificial kidney; dialysis fluid sodium concentration was 133 mEq/liter; potassium, 2.0 mEq/liter. A low transmembrane pressure (5-10 cm H2O) was used to achieve minimal sodium and water removal. On day 2 the first incremental angiotensin II infusion was carried out, after which dietary sodium intake was reduced to between 10 and 17 mEq daily. Potassium and protein intake were maintained at the original level. On day 4 the second hemodialysis was performed. On this occasion a high transmembrane pressure (20-30 cm H2O) was used to achieve maximal sodium and water removal; dialysis fluid composition was as for the first hemodialysis. Heparin (10,000-14,000 U) was administered intravenously between 8 and 9 a.m. after the subjects had fasted and lain supine for 8-12 hours. Throughout the infusions the subjects were given a 5% dextrose at a rate of 4 ml/hr for 60 minutes before the end of each infusion period.

The incremental angiotensin infusions were started between 8 and 9 a.m. after the subjects had fasted and lain supine for 8-12 hours. Throughout the infusions the subjects lay quietly, without sleeping, in an isolated room. Initially, 4 ml/hr for 30 minutes; this was followed by graded doses of Asp1-NH2-Val1-angiotensin II (Ciba) at 2, 4, and 8 ng/kg per min, each for 60 minutes. In four of the subjects (nos. 3, 4, 5, and 6) during the second (sodium-deplete) angiotensin infusion on day 5, an additional dose of 1 ng/kg per min was given for 60 minutes after the control dextrose infusion (Table 2).

Detailed results are presented in Table 2.

Results

Detailed results are presented in Table 2.

BASAL MEASUREMENTS (BEFORE ANGIOTENSIN II INFUSION)

The accurate quantitative assessment of sodium depletion in anephric subjects undergoing hemodialysis is difficult. Since there is a large volume of dialysis fluid (approximately 200 liters), its accurate measurement presents problems, thus small errors in the measurement of dialysate sodium content are magnified. It is easier to demonstrate qualitative sodium depletion. Significant sodium depletion between the first and second angiotensin II infusions in the present study was assumed on the following evidence: All subjects showed a fall in body weight (P < 0.05), in mean arterial pressure (P < 0.05), and in plasma sodium concentration (P < 0.05) when the basal (pre-angiotensin infusion) periods on days 2 and 5 were compared. By contrast, plasma potassium concentration was not significantly altered in these samples.

Before sodium depletion, basal plasma renin concentrations were within the normal range (25-120 µU/ml)** in five subjects and undetectable (< 16 µU/ml) in one. Plasma angiotensin II and aldosterone were within the respective overall normal ranges (5-35 pg/ml and 1-18 ng/100 ml) in subjects and undetectable (< 16 µU/ml) in one. Plasma angiotensin II and aldosterone were within the respective overall normal ranges (5-35 pg/ml and 1-18 ng/100 ml) in

### Table 1 Clinical and Dietary Data

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Cause of renal failure</th>
<th>Interval from nephrectomy</th>
<th>Na (mEq) Intake/24 hr</th>
<th>K (mEq) Intake/24 hr</th>
<th>Protein (g)</th>
<th>Water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>25</td>
<td>Renal tuberculosis</td>
<td>2 yr</td>
<td>45 ± 9</td>
<td>13 ± 11</td>
<td>58 ± 11</td>
<td>46 ± 6</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>22</td>
<td>Chronic pyelonephritis</td>
<td>3 yr</td>
<td>43 ± 10</td>
<td>12 ± 4</td>
<td>45 ± 5</td>
<td>45 ± 5</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>42</td>
<td>Malignant hypertension</td>
<td>5 yr</td>
<td>40 ± 10</td>
<td>15 ± 5</td>
<td>53 ± 10</td>
<td>55 ± 8</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>37</td>
<td>Malignant hypertension</td>
<td>3 wk</td>
<td>28 ± 10</td>
<td>10 ± 6</td>
<td>41 ± 10</td>
<td>41 ± 10</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>37</td>
<td>Chronic pyelonephritis</td>
<td>4 yr</td>
<td>25 ± 10</td>
<td>12 ± 5</td>
<td>45 ± 5</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>28</td>
<td>Goodpasture's syndrome</td>
<td>3 wk</td>
<td>46 ± 10</td>
<td>17 ± 6</td>
<td>56 ± 10</td>
<td>51 ± 10</td>
</tr>
</tbody>
</table>

Means ± SE:

<table>
<thead>
<tr>
<th>Na (mEq)</th>
<th>K (mEq)</th>
<th>Protein (g)</th>
<th>Water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.8 ± 9</td>
<td>13.2 ± 2.5</td>
<td>49.6 ± 6.9</td>
<td>48.0 ± 5.0</td>
</tr>
<tr>
<td>67.5 ± 11.7</td>
<td>10.9 ± 4.1</td>
<td>525 ± 41.8</td>
<td>550 ± 65.1</td>
</tr>
</tbody>
</table>

R = sodium-replete; D = sodium-depleted.
all six subjects (Table 3). Sodium depletion caused no significant changes in basal plasma renin, angiotensin II, cortisol, or aldosterone concentrations. Plasma renin substrate was estimated only in the sodium-replete state (Table 3). Values were normal (0.89-1.22 μmol/liter) for all except subjects 2 and 3, in whom increased concentrations were found (5.31 and 2.10 μmol/liter, respectively).

**EFFECT OF WEIGHT-LOWERING HEMODIALYSIS**

There were no significant differences in the concentrations of plasma angiotensin II and aldosterone in the arterial samples taken on days 4 and 5, i.e., before and after the second hemodialysis.

**EFFECT OF ANGIOTENSIN II INFUSIONS**

*Plasma Angiotensin II.* The mean arterial plasma angiotensin II concentrations at each dose were not significantly different before and after sodium depletion. Doubling the infusion rate roughly doubled the plasma angiotensin II concentration at each increment.

*Plasma Aldosterone.* Before sodium depletion, four subjects showed little or no rise in plasma aldosterone concentration, even at the highest angiotensin II infusion rates, which produced arterial plasma angiotensin II levels 7-10 times the normal upper limit. (In subject 3, the basal value of 7.1 ng/100 ml seemed possibly to be spuriously high. This sample was reextracted and assayed, the result being 6.8 ng/100 ml.) In the remaining two subjects (nos. 1 and 5), a linear increase in plasma aldosterone concentration was apparent with increasing arterial plasma angiotensin II levels (Fig. 1). Even in the two clearly responsive subjects, however, the changes in plasma aldosterone were less for a given arterial plasma angiotensin II concentration than had been found previously in all except one of a series of sodium-replete normal subjects.4,9,10

After sodium depletion, on day 5, one anephric subject (no.3), showed only a marginal response to angiotensin II infusion; in each of the remaining five, however, plasma aldosterone clearly increased during the administration of angiotensin II. There was no obvious relationship between the aldosterone response to angiotensin II and the interval following bilateral nephrectomy (Table 1), although the least responsive subject (no. 3) had been anephric for the longest period (5 years).

In all six subjects plasma aldosterone appeared to reach a plateau at an arterial plasma angiotensin II concentration between 50 and 100 pg/ml (Fig. 1). Increasing the arterial plasma angiotensin II concentration to the range 150-320 pg/ml caused no further rise in aldosterone. This contrasted with the results before sodium depletion in the two subjects (nos. 1 and 5) who were responsive. In these a continuing rise in plasma aldosterone was seen with increasing plasma angiotensin II concentrations to 365 and 232 pg/ml, respectively (Fig. 1 and Table 3). Sodium-depleted normal subjects similarly have been found7 to have progressive increases in plasma aldosterone, with arterial plasma angiotensin II concentrations up to 373 pg/ml, during angiotensin II infusions; basal (preinfusion) arterial angiotensin II levels in these sodium-depleted normals ranged from 28 to 85 pg/ml. Thus in the anephric subjects the dose-response curves after sodium depletion were lower and flatter than in all except one of the sodium-depleted normal subjects studied previously.4,9,10 Nevertheless, in the anephric subjects, as in normal subjects, sodium depletion clearly sensitized the adrenal cortex to angiotensin II. In the present experiments, at each dose rate of angiotensin II which was given in both situations (2, 4, and 8 ng/kg per min), plasma aldosterone was higher after sodium depletion than before in every subject (respectively, P <0.02, <0.05, and <0.01; overall, P < 0.001).

In agreement with our earlier observations,** in the
TABLE 3  Effect of Sodium Status and Angiotensin II Infusion on the Components of the Renin-Angiotensin-Aldosterone System

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Status</th>
<th>Wt (kg)</th>
<th>Plasma renin conc. (µU/ml)</th>
<th>Plasma renin substrate (µmol/liter)</th>
<th>Plasma angiotensin II (pg/ml)</th>
<th>Plasma aldosterone (ng/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 R</td>
<td>34.2</td>
<td>32</td>
<td>0.89</td>
<td>23</td>
<td>*</td>
<td>67</td>
</tr>
<tr>
<td>2 R</td>
<td>34.0</td>
<td>37</td>
<td>*</td>
<td>16</td>
<td>*</td>
<td>65</td>
</tr>
<tr>
<td>3 R</td>
<td>52.8</td>
<td>79</td>
<td>5.31</td>
<td>41</td>
<td>*</td>
<td>61</td>
</tr>
<tr>
<td>4 R</td>
<td>52.1</td>
<td>63</td>
<td>*</td>
<td>39</td>
<td>*</td>
<td>57</td>
</tr>
<tr>
<td>5 R</td>
<td>75.5</td>
<td>42</td>
<td>2.10</td>
<td>30</td>
<td>*</td>
<td>88</td>
</tr>
<tr>
<td>6 R</td>
<td>73.1</td>
<td>63</td>
<td>*</td>
<td>22</td>
<td>*</td>
<td>64</td>
</tr>
<tr>
<td>7 R</td>
<td>50.5</td>
<td>&lt;16</td>
<td>1.22</td>
<td>16</td>
<td>*</td>
<td>96</td>
</tr>
<tr>
<td>8 R</td>
<td>48.6</td>
<td>&lt;16</td>
<td>*</td>
<td>10</td>
<td>52</td>
<td>112</td>
</tr>
<tr>
<td>9 R</td>
<td>52.0</td>
<td>95</td>
<td>1.11</td>
<td>13</td>
<td>*</td>
<td>38</td>
</tr>
<tr>
<td>10 R</td>
<td>50.6</td>
<td>63</td>
<td>*</td>
<td>11</td>
<td>42</td>
<td>52</td>
</tr>
<tr>
<td>11 R</td>
<td>70.7</td>
<td>21</td>
<td>*</td>
<td>16</td>
<td>22</td>
<td>120</td>
</tr>
<tr>
<td>12 R</td>
<td>66.8</td>
<td>42</td>
<td>*</td>
<td>18</td>
<td>39</td>
<td>56</td>
</tr>
</tbody>
</table>

Means ± SD

R = sodium-replete; D = sodium-depleted.

Immediately before the sodium-depleting dialysis plasma angiotensin II concentrations for subjects 2-6 were 44, 27, 11, 13, and 14 pg/ml, respectively (mean, 21.8 ± 13.9 SD), and plasma aldosterone concentrations for subjects 2-6 were 2.0, 1.7, 6.6, 15.6, and 6.7 ng/100 ml, respectively (mean, 6.3 ± 5.6 SD).

* No measurement made.

sodium-depleted anephric subjects, at the highest dose of angiotensin II the increments of plasma aldosterone were proportional to the basal (preinfusion) aldosterone level \( r = +0.73 \). With the small numbers studied this was not statistically significant \( P > 0.05 \).

Plasma Cortisol. No significant differences were found in plasma cortisol levels before and after sodium depletion at any of the angiotensin II infusion rates. At infusion rates of 0, 2, 4, and 8 ng/kg per min of angiotensin II, plasma cortisol concentrations were (mean ± SD) 7.7 ± 6.6, 5.4 ± 4.8, 4.5 ± 3.7, and 5.0 ± 3.6 µg/100 ml, respectively, in the sodium-replete state, and 6.3 ± 3.3, 4.5 ± 2.8, 4.9 ± 4.2, and 4.0 ± 4.0 µg/100 ml, respectively, in the sodium-deplete state.

Changes in Plasma Electrolytes. When only those subjects not showing an obvious aldosterone response to angiotensin II were considered (subjects 2, 3, 4, and 6, first angiotensin II infusion; subject 3, second infusion), angiotensin II adminis-

**FIGURE 1** Angiotensin II/aldosterone log dose-response curves before (●) and after (○) sodium deprivation for the six subjects. The lowest point on each curve is the basal (preinfusion) relationship. A log scale is used on the abscissa.
ANGIOTENSIN II INFUSION IN ANEPHRIC MAN/Deheneffe et al.

Conversely, when, in the anephric subjects, absolute values of blood pressure were plotted against arterial angiotensin II concentrations, the curve of sodium depletion was shifted significantly downward ($t = 5.6; P < 0.001$) (Fig. 4).

Discussion

After bilateral nephrectomy, plasma angiotensin II concentrations were measurable in all subjects, and renin concentrations were measurable in five of the six subjects, most of the values being within normal ranges. Angiotensin II levels were highest in the two subjects with raised levels of renin substrate, one of these being the woman taking an oral contraceptive. Many previous studies, employing a variety of techniques, have shown the presence of a renin-like enzyme, together with immunoreactive substances resembling angiotensin I and angiotensin II in peripheral blood after bilateral nephrectomy. In this department, chromatography of extracts of plasma from anephric subjects has shown a peak of angiotensin II-like immunoreactive material running at a rate indistinguishable from that of authentic angiotensin II. In those reports in which there has been failure to detect renin or renin activity, a possible explanation is the use of relatively insensitive assay methods. Organs other than the kidney in which renin-like enzymes have been found include the uterus, salivary glands, adrenal cortex, arterial walls, and central nervous system. Renin could be released from any or all of these into the blood in the anephric subject.

Effective sodium depletion between the first and second angiotensin II infusions in the present experiments was inferred from the combination of weight loss, fall in plasma sodium concentration, and reduction of arterial pressure, although, for the reasons already discussed, the magnitude of this could not be measured accurately. There was no change in the concentrations of renin and angiotensin II after sodium depletion, confirming the earlier finding reported by Yu et al. in a single subject. Thus, peripheral plasma renin and angiotensin II concentrations in the
anephric state are unaffected by changes in sodium balance and permit a study of the effects of sodium depletion in the absence of changes in endogenous angiotensin II concentration. The fall in plasma sodium with sodium deprivation in the absence of a change in plasma angiotensin II is noteworthy, as earlier it had been suggested that a rise in angiotensin II might be responsible for this effect.

In the present experiments, infused angiotensin II was the Asp'-NH,-Val' form; it has been shown that in man there is no detectable difference in the pressor- and aldosterone-stimulating properties between this and the naturally occurring Ileu' form. No evidence was obtained that sodium depletion in the anephric subject altered the metabolic clearance of angiotensin II, in that mean plasma angiotensin II levels were not significantly different before and after sodium depletion at each infusion rate.

Previous observations on normal and anephric man, have failed to demonstrate changes in the clearance rate of aldosterone during sodium depletion or angiotensin II infusion, although one study has shown unexpectedly high absolute clearance rates in anephric subjects. A possible reason for an increase in plasma aldosterone concentration is a reduction in plasma volume. However, basal plasma aldosterone values were not significantly different before and after dietary sodium restriction or before and after weight-reducing hemodialysis (Table 3). Moreover, a simple effect of a decrease in plasma volume on aldosterone concentration would be a parallel upward shift of the dose-response curve of aldosterone to angiotensin II, and this was not the case (Fig. 1). Thus, the observed changes in plasma aldosterone during angiotensin II administration probably reflected changes in aldosterone secretion rate.

The evidence shows, therefore, that in these anephric subjects, sodium depletion produced sensitization of the adrenocortical aldosterone response to angiotensin II. Since this sensitization occurred in the absence of changes in endogenous angiotensin II, it could not be the result of a trophic action of increased levels of angiotensin II on the adrenal cortex. Although evidence in favor of such a trophic action has been obtained for normal subjects, even then it provides only a partial explanation.

At the same time, in the anephric subjects, the adrenocortical response to angiotensin II, both before and after sodium depletion, was less than that of nearly all normal subjects. In all the anephric subjects, there was a maximum plasma aldosterone concentration which was not exceeded despite considerable further elevation of plasma angiotensin II. This difference could be due to loss of a trophic action of angiotensin II, or of some other factor of renal origin. In the anephric subjects the measured levels of endogenous angiotensin II were within the normal range, but it is not clear whether such immunoreactive material is biologically active. Damping of adrenocortical response might also result from damage to the adrenals at the time of bilateral nephrectomy but the relatively normal levels of cortisol argue against this.

Heparin and heparinoids may interfere with aldosterone biosynthesis. However, in studies of three subjects with chronic renal failure undergoing regular hemodialysis but with kidneys remaining, according to the same protocol as in the present studies, we found no impairment of the plasma aldosterone response to angiotensin II either before or after sodium depletion, as compared with normal subjects. Bayard et al. similarly found that heparin administration did not interfere with aldosterone secretion in anephric man. The diminished response of aldosterone to angiotensin II appears to be related to bilateral nephrectomy.

In the present studies we obtained no evidence that the enhanced adrenocortical sensitivity following sodium deprivation was related to changes in ACTH secretion, in that plasma cortisol levels, basal and during angiotensin II administration, were unchanged by alterations in sodium balance. This observation is subject to the important caveat that plasma cortisol may not necessarily reflect changes in ACTH, particularly during angiotensin II administration. Plasma potassium concentrations were not significantly different before and after sodium depletion: Cooke et al. have shown that in anephric man plasma aldosterone concentrations can be affected by changes in plasma potas-
sium in the absence of changes in external potassium balance. Plasma sodium concentration was lower following sodium depletion; this, possibly combined with other more subtle effects of sodium depletion on the adrenal gland, might be the factor involved. For instance, Baumber et al.**3; however, when absolute levels of arterial pressure are absolute level of blood pressure at which an otherwise normal angiotensin II response occurs. Plotting the increment of blood pressure against the prevailing arterial plasma angiotensin II concentration shows no difference between sodium depletion and plasma angiotensin II concentration were normal; after sodium depletion plasma angiotensin II concentration did not change and blood pressure fell. This contrasts with the situation in normal man, where sodium depletion leads to a rise in circulating angiotensin II with little or no change of blood pressure.**8 The pressor effect of a given arterial plasma angiotensin II concentration in anephric man. Circ Res 34: 69-77, 1974
Response of aldosterone and blood pressure to angiotensin II infusion in anephric man.
Effect of sodium deprivation.
J Deheneffe, V Cuesta, J D Briggs, J J Brown, R Fraser, A F Lever, J J Morton, I S Robertson and M Tree

Circ Res. 1976;39:183-190
doi: 10.1161/01.RES.39.2.183

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/39/2/183