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Apparent acid retention was found throughout the studies during acidosis, despite no further reduction of the serum bicarbonate concentration. The negative calcium balances that accompanied acid retention support the suggestion that slow titration of alkaline bone salts provides an additional buffer reservoir in chronic metabolic acidosis. The treatment of metabolic acidosis prevented further calcium losses but did not induce net calcium retention. It is suggested that the normal homeostatic responses of the body to the alterations in ionized calcium and calcium distribution produced by raising the serum bicarbonate might paradoxically retard the repair of skeletal calcium deficits.
The Effect of Treatment of Acidosis on Calcium Balance in Patients with Chronic Azotemic Renal Disease *

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Summary. Small but statistically significant negative calcium balances were found in each of eight studies in seven patients with chronic azotemic renal disease when stable metabolic acidosis was present. Only small quantities of calcium were excreted in the urine, but fecal calcium excretion equaled or exceeded dietary intake. Complete and continuous correction of acidosis by NaHCO₃ therapy reduced both urinary and fecal calcium excretion and produced a daily calcium balance indistinguishable from zero.

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Introduction

Skeletal abnormalities may occur in the course of chronic azotemic renal disease. Osteomalacia, osteitis fibrosa, and osteosclerosis may be recognized by X ray, singly or in combination, and are found with greater frequency on histologic examination of bone (1–3). Chronic metabolic acidosis, acquired vitamin D resistance, and secondary hyperparathyroidism have each been con-

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considered a factor in the pathogenesis of these disorders (1, 4, 5).

The role of metabolic acidosis has not been critically tested. Although Albright and Reifenstein considered acidosis the major cause of azotemic bone disease (4), other studies (2, 5, 6) have failed to find calcium retention after alkali therapy. Such studies have often been brief, and alkali therapy has frequently been continued while other forms of therapy were evaluated.

We carried out the present studies to determine whether the continuous and complete correction of the acidosis of chronic renal disease had any significant influence on calcium balance.

Methods

Eight paired metabolic balance studies were carried out in seven patients with chronic azotemic renal disease during periods of spontaneous but stable acidosis and during periods when the serum bicarbonate concentration was maintained at stable normal levels by the continuous administration of sodium bicarbonate. None
of the subjects' serum bicarbonate concentrations changed by more than ±1 mEq per L on the eight or more determinations during each of the separate parts of the paired studies. Each phase of the study of every patient consisted of three or four consecutive 6-day metabolic periods. All patients were hospitalized in the Clinical Research Center, Marquette University School of Medicine, and each patient ate a constant diet. Six of the studies were carried out first while the patient was acidic and then repeated after at least 2 weeks of NaHCO₃ therapy. Two studies were carried out in patients who had been receiving adequate NaHCO₃ therapy for many months and were repeated several weeks after alkali therapy had been stopped. Table I presents the pertinent clinical data for each patient. All but one had radiographic evidence of slight diffuse demineralization of bone, and three had changes consistent with secondary hyperparathyroidism (subperiosteal bone resorption in phalanges). None had significant bacteriuria.

Each patient was allowed 3 to 6 days to adapt to his constant diet before balance observations were begun. The diets were typical of ordinary American diets and were adjusted to the patient's customary food intake. Duplicate daily diets were prepared and analyzed on eight to twelve occasions during each study. The average coefficient of variation for the analyses of each diet constituent was as follows: Na, ± 4.1%; K, ± 4.4%; Ca, ± 4.2%; Mg, ± 4.3%; Cl, ± 4.0%; and P, ± 4.7%.

The constant daily doses of NaHCO₃ required to maintain normal stable serum bicarbonate levels were weighed on an analytical balance and administered in gelatin capsules in four divided daily doses. Sodium bicarbonate doses of 61 to 180 mEq per day were required to maintain normal serum bicarbonate levels because of the variable reduction in renal tubular reabsorptive threshold for bicarbonate in patients with renal disease (7). Each patient received one multivitamin capsule daily containing 1,000 USP U of vitamin D.

In five paired studies the patients were given 10.0 mEq of stable strontium as the gluconate¹ intravenously at the beginning of a metabolic period while acidic and again when the serum bicarbonate was kept at steady normal levels by NaHCO₃ therapy. Strontium was measured in serum, urine, and fecal ash by atomic absorption spectrophotometry with lanthanum in the diluent to suppress anionic interference. We carried out all strontium analyses for both phases of the study of each patient simultaneously to minimize analytical variability. Strontium was administered with the intention of estimating calcium turnover in bone by the method described by Fraser, Harrison, and Ibbertson (8). The validity of the use of strontium as a tracer for bone calcium turnover has been documented by other investigators (9, 10) as well. The calculations used by Fraser and co-workers (8) depend upon the fact that normal subjects excrete most of an injected dose of strontium in the urine. In their studies, normal subjects excreted only 8 to 16% of a 10-mEq intravenous dose of strontium in

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¹ Kindly supplied by Dr. C. D. Burrell, Sandoz Pharmaceuticals, Hanover, N. J.
the feces during the first 6 days after injection, and this was neglected in their kinetic analyses. Studies in our laboratory of two normal subjects who were given 10 mEq of strontium intravenously showed that they excreted 33 and 38% of the dose in the urine in 6 days and 8 and 10% in the feces during the same period. By contrast, the patients with renal disease excreted, at most, 14% of the dose of strontium in the urine while excreting as much of the dose in the feces as did normal subjects. Thus, kinetic analyses of these data could not be carried out because strontium was excreted primarily in the feces, and the excretion into the gut on a given day of the study could not be determined accurately because of the variable lag between fecal formation and defecation. Nevertheless, it was possible to compare the amount of strontium retained in the body 6 days after injection and the corresponding serum strontium concentrations in the same subject before and after treatment of acidosis. Alkali therapy had no apparent effect on the frequency of defecation or the quantity of feces excreted per 6-day metabolic period. During those periods in which strontium was injected, average daily stool weight was 119 ± 38 g during acidosis and 116 ± 30 g during alkali therapy.

All other procedures, analytical methods, and calculations have been described in a previous publication (11). As in our earlier studies, carmine markers were used to delineate stool periods. All experimental results are presented as mean values ± 1 SD.

### Results

The average concentrations of blood and serum constituents during stable acidosis and after bicarbonate therapy are presented in Table II. Alkali therapy significantly reduced blood [H+] and raised serum [HCO₃⁻]. Compensatory reductions in CO₂ pressure (P<sub>CO₂</sub>) and [Cl⁻] occurred. "Unmeasured anions"<sup>2</sup> rose significantly, presumably because the anionic charges of the serum proteins increased. The remaining electrolyte concentrations and the serum creatinine concentrations did not change.

The mean values for the diet analyses are shown in the upper part of Table III. Sodium and

<sup>2</sup> [Na⁺] - ([Cl⁻] + [HCO₃⁻]).
chloride intakes differed in the two parts of each study because the quantity of NaCl added to the diets was reduced when NaHCO₃ therapy was begun. The mean values for the remainder of the diet analyses were not different. The mean stool weight and fecal electrolyte contents are shown in the lower part of Table III. No significant changes occurred.

The average changes in body weight and the mean balances of Na, K, Mg, Cl, and P during acidosis and after alkali therapy are presented in Table IV. No significant changes were found.

The most pertinent findings in each of the paired studies are shown in Table V. The values given for each patient during acidosis and during alkali therapy are the means of all metabolic periods observed in that study. The first three columns show that mild to moderate acidosis was present in each patient before therapy, and that the serum [HCO₃⁻] was normal during NaHCO₃ therapy. The mean change in serum [HCO₃⁻] after alkali therapy was +8.7 ± 3.5 mEq per L (p < 0.001). The effect of alkali therapy on calcium balance is shown in the next three columns. During acidosis, small negative calcium balances were observed in each study, averaging −5.3 ± 3.8 mEq per day. This differed significantly from zero balance (p < 0.01). With NaHCO₃ therapy, calcium balance was less negative in six of the eight studies, and, for the group, was no longer significantly different from zero balance (p > 0.3). The mean change in calcium balance after alkali therapy was significant (p = 0.025). The urinary calcium excretion (not shown in the Table) was very low in both parts of each study, averaging 1.7 ± 0.9 mEq per day during acidosis and 1.5 ± 0.9 mEq per day during alkali therapy.

The next three columns of Table V give the percent of a 10-mEq intravenous dose of strontium retained 6 days after injection in each of five patients while acidic and again after NaHCO₃ therapy. Each patient retained more of the strontium after alkali therapy; despite this the serum concentration of strontium 6 days after administration (shown in the next three columns) was lower. The cumulative urinary strontium excretion (not shown in the Table) was low, averaging 9 ± 5% of the dose during acidosis and 6 ± 3% during alkali therapy. Most of the strontium appeared in the feces (18 ± 6% of the dose during acidosis and 12 ± 3% when the serum bicarbonate was normal).

The final three columns of Table V show the apparent net external acid balances, calculated as described previously (11). The mean acid balance in each phase of the studies was not significantly different from zero, but the change in acid balance between the paired studies was significant (p < 0.01). In seven of the eight studies acid balance was less positive during alkali therapy.

The parameters of acid balance for the group are presented in Table VI. During alkali therapy, the sum of urinary SO₄²⁻ and organic acid salts increased significantly, due entirely to an increase in the amount of total organic acids existing as anions in the more alkaline urines. The calculated dietary and stool combustible anions were unchanged. Net fixed acid production, including the NaHCO₃ administered, was significantly reduced. Renal acid excretion also fell significantly as a result of losses of bicarbonate in the urine during alkali therapy. However, the reduction in acid excretion during alkali therapy was not so great as the reduction in acid production, and thus the acid balance was significantly less positive.
### TABLE V
The major effects of alkali therapy in patients with chronic azotemic renal disease

<table>
<thead>
<tr>
<th>Patient</th>
<th>Serum HCO₃⁻</th>
<th>Calcium balance</th>
<th>Strontium retention†</th>
<th>Serum strontium‡</th>
<th>Acid balance§</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acidosis</td>
<td>Alkali therapy</td>
<td>Δ*</td>
<td>Acidosis</td>
<td>Alkali therapy</td>
</tr>
<tr>
<td></td>
<td>mEq/L</td>
<td></td>
<td>mEq/day</td>
<td>%</td>
<td>mEq/L</td>
</tr>
<tr>
<td>MvL</td>
<td>15.4</td>
<td>29.3</td>
<td>+13.9</td>
<td>-6.0</td>
<td>-1.3</td>
</tr>
<tr>
<td>C.D.</td>
<td>19.7</td>
<td>29.7</td>
<td>+10.0</td>
<td>-7.8</td>
<td>-4.0</td>
</tr>
<tr>
<td>E.J.</td>
<td>23.2</td>
<td>27.2</td>
<td>+4.0</td>
<td>-1.8</td>
<td>+0.2</td>
</tr>
<tr>
<td>C.C.</td>
<td>18.9</td>
<td>30.3</td>
<td>+11.4</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>C.J.</td>
<td>14.0</td>
<td>25.6</td>
<td>+11.6</td>
<td>-3.0</td>
<td>+0.2</td>
</tr>
<tr>
<td>E.J.</td>
<td>17.5</td>
<td>25.2</td>
<td>+7.7</td>
<td>-10.2</td>
<td>+1.0</td>
</tr>
<tr>
<td>B.B.</td>
<td>18.4</td>
<td>24.8</td>
<td>+6.4</td>
<td>-10.2</td>
<td>-11.0</td>
</tr>
<tr>
<td>L.B.</td>
<td>22.5</td>
<td>27.3</td>
<td>+4.8</td>
<td>-1.8</td>
<td>+4.2</td>
</tr>
</tbody>
</table>

Mean ± SD: 18.7 ± 3.2 27.4 ± 2.1 8.7 ± 3.5 -5.3 ± 3.8 -1.5 ± 4.5 ±3.8 ± 3.8 73 ± 9 82 ± 4 ±9 ± 6 0.067 ± 0.011 0.061 ± 0.014 -0.006 ± 0.005 +10 ± 13 -2 ± 15 -12 ± 9

p: <0.001 <0.01 >0.3 0.025 <0.025 <0.05 >0.1 >0.50 <0.01

† Percentage of a 10-mEq dose retained 6 days after intravenous injection [dose injected - (total urinary and fecal excretion)/dose injected].
‡ Serum level 6 days after strontium administration.
§ Calculated as [(urinary SO₄+ OA salts) - (diet combustible anions - stool combustible anions)] - [(urinary NH₄+ + calculated titratable acid) - urinary HCO₃⁻]. OA = organic acid.

* Value during alkali therapy minus value during acidosis.

Discussion

A negative calcium balance was found in each patient with chronic azotemic renal disease when stable metabolic acidosis was present. As in other studies of calcium metabolism in acido-me
tics and azotemic subjects, the patients excreted little acido-metabolite calcium and little acido-metabolite calcium was excreted. The patients excreted a small amount of acido-
metabolite calcium in the urine (22), but fecal excretion of calcium was low in these patients. It is likely that such losses are due to physiological significance in the potential duration of calcium deficiency.

These results suggest that the correction of metabolic acidosis was achieved by increasing calcium absorption and retention in the skeleton of an average adult. When the renal loss of calcium is considered, the daily loss of 5.3 ± 3.8 mEq/kg body weight is statistically significant. With the potential duration of calcium deficiency is considered, the likelihood of such losses is increased. Projected over 10 years, the rate of potential duration of calcium deficiency is 5.3 ± 3.8 mEq/kg body weight. It is likely that such losses are due to physiological significance in the potential duration of calcium deficiency.
skeletal remineralization. As Heaney has recently stressed (15), the hormonal control of calcium metabolism in the adult appears to defend primarily the ionized calcium concentration of body fluids. When metabolic acidosis is treated with alkali, both redosposition of calcium in bone and an increased affinity of plasma proteins for calcium would tend to lower the serum ionized calcium concentration. This change would presumably be opposed by increased parathyroid hormone secretion, with a resultant increase in intestinal and renal tubular calcium reabsorption, but also an increased mobilization of calcium from bone. The effect of parathyroid hormone on bone itself, although aiding in the stabilization of the blood ionized calcium concentration, would paradoxically retard the repair of skeletal calcium deficits. By contrast, the primary action of pharmacologic doses of vitamin D (2, 5, 6) or massive oral administration of calcium salts (16) would be to increase intestinal calcium absorption. In this circumstance, serum ionized calcium would tend to rise, parathyroid hormone secretion would decrease, and deposition of calcium in bone would be favored.

Regardless of the intimate mechanisms, the results of the present studies are consistent with a previous suggestion (17) that slow losses of calcium from the skeleton might occur in chronic azotemic renal disease while acidosis was present, but not when the acidosis was adequately treated. As in earlier investigations (17, 18), an apparent continuing retention of acid was found during periods when the serum \([\text{HCO}_3^-]\) was reduced but stable. If it is assumed that the actual acid balance was zero during alkali therapy (18), the apparent acid retention during acidosis averaged 12 ± 9 mEq per day. The simultaneous losses of calcium, regardless of the salts from which they arose, could not account for the retention of this quantity of acid. It is most likely that this quantitative discrepancy resulted from difficulties inherent in calculating acid production when whole food diets were used (11). An alternative possibility is that the valence of phosphorus in the feces increased significantly during acidosis in these azotemic patients, and fecal losses of combustible anions were thus overestimated.

**References**


