Increased calcium intake reduces plasma cholesterol and improves vasorelaxation in experimental renal failure

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Chronic renal failure (CRF) is associated with various vascular complications and abnormal lipid metabolism (2, 16). Among CRF patients, cardiovascular disease is a major cause of morbidity, leading to a 20-fold increased risk of cardiovascular death compared with healthy controls (1, 16). However, the pathophysiological mechanisms affecting the arteries and contributing to the development of the vasculopathic state are still poorly understood.

The present study was designed to test the phosphate-binding hypothesis and whether phosphate binding and prevention of the development of secondary hyperparathyroidism by a high-calcium diet can also reduce plasma cholesterol levels in experimental renal failure.

Increased calcium intake reduces plasma cholesterol and improves vasorelaxation in experimental renal failure.
CRF, and whether these changes are reflected as alterations in the control of resistance artery tone.

METHODS

Animals and experimental design. Male Sprague-Dawley rats (n = 42; n = 18 in additional extended follow up) were housed two to a cage with access to water and food (AnalyCen; Lindköping, Sweden). Systolic blood pressures (rat age 8 wk) were measured at +28°C with a tail-cuff blood pressure meter (model 129; IITC; Woodland Hills, CA). Surgical procedures were performed under ketamine/diazepam anesthesia (75 and 2.5 mg/kg ip, respectively). In the 5/6 nephrectomized (NTX) groups, the upper and lower poles of the left kidney were cut off, and the right kidney was removed (38). In the sham groups, both kidneys were decapsulated. Antibiotics (60 mg/kg metronidazole and 225 mg/kg cefuroxim) were given postoperatively, and pain was relieved with buprenorphine (0.2 mg/kg subcutaneously) three times the 5/6 nephrectomy surgery. Both kidneys were decapsulated (75 and 2.5 mg/kg ip, respectively). In the 5/6 nephrectomized (NTX) groups, the upper and lower poles of the left kidney were cut off, and the right kidney was removed (38). In the sham groups, both kidneys were decapsulated. Antibiotics (60 mg/kg metronidazole and 225 mg/kg cefuroxim) were given postoperatively, and pain was relieved with buprenorphine (0.2 mg/kg subcutaneously) three times. Cefuroxim) were given postoperatively, and pain was relieved with buprenorphine (0.2 mg/kg subcutaneously) three times.

Calcium, NTX, and NTX-Calcium; 95% O2-5% CO2. Normalization of the vascular preparations was performed by a clear relaxation to 1 μM ACh in 5 μM norepinephrine (NE)-precontracted rings and the absence of endothelium by the lack of this response. The endothelium was removed by perfusing air through the lumen.

Arterial contractions to NE and endothelium-mediated relaxations in endothelium-intact small arteries. Contractions to NE (0.1–10 μM) were first cumulatively determined. Thereafter relaxations to ACh (1 nM–10 μM) were examined in arteries precontracted with 5 μM NE, which resulted in ~80% of the maximal contractile response attained in both groups. The rings were allowed a 30-min equilibration period in PSS between each cumulative response.

Arterial contractions to KCl and endothelium-independent relaxations to exogenous nitric oxide (endothelium-denuded small arteries). Contractions to increasing concentrations of KCl were determined, and in solutions containing high concentrations of K+ (20–125 mM) NaCl was replaced with KCl on an equimolar basis. Relaxations to 1 nM-10 μM nitroprusside [nitric oxide (NO) donor] were examined in rings precontracted with 5 μM NE. The preparations were allowed a 30-min equilibration period in PSS between each relaxation.

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between plasma levels of cholesterol, LDL, HDL-to-LDL (HDL/LDL ratio), PTH, phosphate, ionized calcium, and the pD<sub>2</sub> values for ACh in subtotally nephrectomized rats. The results from sham-operated animals were excluded from the scatterplots because increased calcium intake had no effect on arterial tone in these animals.

Statistical analysis was carried out by one- and two-way ANOVA supported by the Bonferroni test when carrying out pairwise comparisons between the test groups. ANOVA for repeated measurements was applied for data consisting of repeated observations at successive time points. Results are expressed as means ± SE, and the differences were considered significant when \( P < 0.05 \). Unless otherwise indicated, the \( P \) values in the text refer to ANOVA for repeated measurements. In the subtotally nephrectomized rats, correlation analyses were also performed between plasma levels of creatinine, urea, and the pD<sub>2</sub> values for ACh. Spearman’s correlation coefficient (\( r_s \); two tailed) was calculated, which was considered significant when \( P < 0.05 \).

**Drugs.** The following drugs were used: ketamine (Parke-Davis Scandinavia; Solna, Sweden), cefuroxim, diazepam (Omeo Pharmra; Espoo, Finland), metronidazole (Braun; Melsungen, Germany), buprenorphine (Reckitt and Colman; Hull, UK), acetylcysteine chloride, norepinephrine bitartrate (Sigma; St. Louis, MO), and sodium nitroprusside (Fluka Chemie; Buchs, Switzerland). Stock solutions were created by dissolving the compounds in distilled water. All solutions were freshly prepared before use and protected from light.

**RESULTS**

**Blood pressure, body and heart weights, total renal mass, drinking fluid, and urine volumes.** Systolic blood pressures and body weights in individual study groups did not differ during the 12-wk follow up. However, when analyzed by two-way ANOVA, a modest but significant increase in blood pressure was observed in subtotally nephrectomized rats versus sham-operated controls: the mean systolic blood pressure values were 150.3 ± 2.7 mmHg in the two NTX groups, and 140.4 ± 2.9 mmHg in the two Sham groups (\( P = 0.018 \)). The outcome of two-way ANOVA was also that increased calcium intake did not significantly influence blood pressure in this study (\( P = 0.12 \)). Renal mass was ~30% lower in both NTX groups than the weight of the two kidneys in sham-operated rats. At the end of the study, the intake of drinking fluid and the output of urine were higher in the NTX rats when compared with the Sham rats (Table 1).

**Laboratory findings.** Plasma total cholesterol and HDL and LDL cholesterol levels were elevated in the NTX group but normalized by calcium supplementation (Fig. 1). Plasma concentrations of creatinine, urea nitrogen, PTH, and phosphate values were increased, whereas hemoglobin, ionized Ca<sup>2+</sup>, and protein concentrations were decreased in the NTX group when compared with the Sham group (Table 1 and Fig. 2). A high-calcium diet elevated plasma ionized Ca<sup>2+</sup> and suppressed plasma phosphate and PTH in both NTX and Sham rats (Fig. 2). No changes were detected in plasma potassium or sodium concentrations (Table 1). Although plasma levels of active vitamin D in individual study groups did not significantly differ, analyses by two-way ANOVA showed that plasma 1,25(OH)<sub>2</sub>D<sub>3</sub> was slightly but significantly lower in the NTX groups than the Sham groups (34.8 ± 1.8 vs. 40.4 ± 2.0 pg/ml, respectively, \( P = 0.049 \)).

**Morphology of small arteries and thoracic aorta.** The resistance arteries showed no significant differences in lumen diameter or wall thickness between the study groups (Table 2). The cross sections of thoracic aortas from rats that were followed for another 8 wk showed increased calcification in the NTX group, whereas aortic calcification in the NTX-Calcium group did not differ from that in the Sham group (Table 2). The plasma levels of creatinine continued to rise in the NTX groups during the extended follow up (Table 2).

**Responses of small mesenteric arterial preparations.** The relaxations induced by ACh in endothelium-intact NE (5 \( \mu \)M)-precontracted preparations were impaired in the NTX group, whereas the NTX-Calcium and Sham-Calcium groups did not differ from the Sham group (Fig. 3A). The relaxations induced by nitropruss-

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**Table 1. Experimental group data at close of study**

<table>
<thead>
<tr>
<th></th>
<th>Sham</th>
<th>Sham-Calcium</th>
<th>NTX</th>
<th>NTX-Calcium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systolic blood pressure, mmHg</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Week 8</td>
<td>135 ± 6</td>
<td>135 ± 4</td>
<td>138 ± 5</td>
<td>138 ± 4</td>
</tr>
<tr>
<td>Week 12</td>
<td>136 ± 6</td>
<td>136 ± 4</td>
<td>140 ± 4</td>
<td>138 ± 4</td>
</tr>
<tr>
<td>Week 20</td>
<td>142 ± 4</td>
<td>138 ± 4</td>
<td>154 ± 5</td>
<td>146 ± 4</td>
</tr>
<tr>
<td>Body weight, g</td>
<td>460 ± 9</td>
<td>470 ± 16</td>
<td>462 ± 9</td>
<td>465 ± 8</td>
</tr>
<tr>
<td>Heart weight/body weight, g/kg</td>
<td>3.4 ± 0.1</td>
<td>3.4 ± 0.1</td>
<td>3.6 ± 0.1</td>
<td>3.8 ± 0.3</td>
</tr>
<tr>
<td>Total renal mass/body weight, g/kg</td>
<td>6.6 ± 0.1</td>
<td>6.3 ± 0.2</td>
<td>4.8 ± 0.2*</td>
<td>4.3 ± 0.2*</td>
</tr>
<tr>
<td>Fluid intake, ml</td>
<td>23 ± 5</td>
<td>26 ± 2</td>
<td>53 ± 5*</td>
<td>54 ± 6*</td>
</tr>
<tr>
<td>Urine volume, ml</td>
<td>20 ± 4</td>
<td>21 ± 5</td>
<td>45 ± 5*</td>
<td>43 ± 7*</td>
</tr>
<tr>
<td><strong>Plasma</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potassium, mmol/l</td>
<td>3.81 ± 0.18</td>
<td>3.76 ± 0.20</td>
<td>3.86 ± 0.09</td>
<td>3.91 ± 0.21</td>
</tr>
<tr>
<td>Sodium, mmol/l</td>
<td>136.1 ± 0.6</td>
<td>139.2 ± 0.9</td>
<td>138.2 ± 0.8</td>
<td>138.5 ± 0.9</td>
</tr>
<tr>
<td>Creatinine, μmol/l</td>
<td>64.0 ± 3.2</td>
<td>65.1 ± 2.9</td>
<td>99.8 ± 5.1*</td>
<td>96.7 ± 4.5*</td>
</tr>
<tr>
<td>1,25(OH)&lt;sub&gt;2&lt;/sub&gt;D&lt;sub&gt;3&lt;/sub&gt;, pg/ml</td>
<td>36.8 ± 2.1</td>
<td>42.2 ± 3.5</td>
<td>34.4 ± 1.2</td>
<td>35.1 ± 3.2</td>
</tr>
<tr>
<td>Proteins, g/l</td>
<td>61.01 ± 0.69</td>
<td>61.88 ± 0.41</td>
<td>57.11 ± 0.98*</td>
<td>56.73 ± 0.71*</td>
</tr>
<tr>
<td>Hemoglobin, g/l</td>
<td>183.1 ± 2.2</td>
<td>178.3 ± 3.9</td>
<td>163.9 ± 4.1*</td>
<td>172.8 ± 2.1*</td>
</tr>
</tbody>
</table>

Values are means ± SE; \( n = 10–11 \) animals for all groups, except for \( n = 7 \) animals for active vitamin D \([1,25(OH)\text{D}_3]\) determinations. NTX, nephrectomized. Animals were 20 wk old at the end of the study. *\( P < 0.05 \) compared with the Sham group.
side, a vasodilator acting via formation of exogenous NO, were similar in all study groups (Fig. 3B). The vascular rings of the study groups exhibited similar contractile sensitivity (i.e., pD₂ values) and maximal wall tensions to NE and KCl (Table 2). Therefore, no changes in vasoconstrictor responses were observed in the NTX-Calcium rats that could explain the enhanced vasorelaxation in the arterial rings of these animals.
Table 2. Parameters of contractile responses and lumen diameters of isolated mesenteric arterial rings in experimental groups, and data from extended followup in 12 NTX and 6 sham rats that were followed for further 8 wk (altogether for 20 wk)

<table>
<thead>
<tr>
<th></th>
<th>Sham</th>
<th>Sham-Calcium</th>
<th>NTX</th>
<th>NTX-Calcium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norepinephrine (+E)</td>
<td></td>
<td></td>
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<tr>
<td>( \text{pD}_2 ), (-\log M)</td>
<td>5.61 ± 0.07</td>
<td>5.71 ± 0.05</td>
<td>5.68 ± 0.02</td>
<td>5.73 ± 0.05</td>
</tr>
<tr>
<td>Maximal wall tension, mN/mm</td>
<td>4.70 ± 0.30</td>
<td>4.55 ± 0.21</td>
<td>4.71 ± 0.23</td>
<td>4.82 ± 0.55</td>
</tr>
<tr>
<td>Potassium chloride (-E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{pD}_2 ), (-\log M)</td>
<td>1.72 ± 0.02</td>
<td>1.70 ± 0.03</td>
<td>1.73 ± 0.01</td>
<td>1.75 ± 0.01</td>
</tr>
<tr>
<td>Maximal wall tension, mN/mm</td>
<td>4.92 ± 0.67</td>
<td>5.06 ± 0.61</td>
<td>5.42 ± 0.87</td>
<td>5.29 ± 0.61</td>
</tr>
<tr>
<td>Morphology at 90 mmHg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall thickness, ( \mu m )</td>
<td>22.9 ± 1.5</td>
<td>23.5 ± 1.4</td>
<td>25.8 ± 1.8</td>
<td>25.0 ± 1.8</td>
</tr>
<tr>
<td>Lumen diameter, ( \mu m )</td>
<td>277 ± 7</td>
<td>271 ± 3</td>
<td>281 ± 8</td>
<td>275 ± 5</td>
</tr>
<tr>
<td>Data from extended 20-wk followup</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma creatinine, ( \mu \text{mol/l} )</td>
<td>69.0 ± 2.7</td>
<td>Not studied 142.0 ± 14.5*</td>
<td>137.0 ± 6.7*</td>
<td></td>
</tr>
<tr>
<td>Aortic calcification, % of the area of aortic cross-section</td>
<td>0.0 ± 0.0</td>
<td>Not studied 7.2 ± 2.4a</td>
<td>0.0 ± 0.0†</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE; \( n = 10–11 \) for other groups, but \( n = 6 \) in the extended 20-wk followup. +E and −E, endothelium intact and endothelium-denuded arterial rings, respectively. \( \text{pD}_2 \) is the negative logarithm of the concentration of agonist producing 50% of maximal contractile force. * \( P < 0.05 \) compared with the sham group; † \( P < 0.05 \) compared with the NTX group.

The present results showed that increased calcium intake, which reduced plasma phosphate and PTH and elevated plasma ionized calcium in NTX rats as expected, was also associated with favorable changes in the lipid profile and endothelium-dependent relaxation of resistance arteries. The scatterplots depicting the variables of plasma lipid profile and calcium-phosphorus metabolism in relation to the sensitivity of resistance arteries to endothelium-dependent vasorelaxation are illustrated in Fig. 4. These scatterplots showed clear clustering of data points in separate subgroups in the NTX and NTX-Calcium groups. Renal function was not different in the two NTX groups, and plasma creatinine and urea showed no correlation to the sensitivity to ACh in the NTX and NTX + Calcium groups \((r = -0.255 \text{ and } -0.186; P = 0.307 \text{ and } P = 0.445, \text{ respectively})\).

**DISCUSSION**

In the present study, renal failure was induced in rats by 5/6 nephrectomy, and the subsequent 1.6- and 1.7-fold elevations in plasma creatinine and urea nitrogen, respectively, were comparable to those observed previously \((13)\). The intake of drinking fluid and the output of urine were increased in the renal failure rats, suggesting a deteriorated urine concentration capacity in the remnant kidney.

Plasma total cholesterol and LDL levels were significantly increased in the NTX group, whereas a high-calcium diet normalized the total and LDL cholesterol levels. The HDL/LDL ratio was also reduced in experimental renal failure but was normalized by high-calcium intake. Plasma triglyceride levels were comparable between the groups. These results correspond to previous findings concerning calcium intake and plasma cholesterol levels in both humans and experimental animals \((14, 34, 37)\). The lipid-lowering effect of dietary calcium probably results from the ability of Ca\(^{2+}\) to bind bile acids and saturated fatty acids in the intestine and form inabsorbable chelates thereby increasing the fecal excretion of these compounds \((7, 34)\).
The mechanisms of the detrimental effect of CRF on plasma cholesterol have also been elucidated previously. It is known that in the rat CRF is associated with down-regulation of hepatic lecithin:cholesterol acyltransferase (LCAT) gene expression and reduction of plasma LCAT activity, as well as upregulation of hepatic acyl-CoA:cholesterol acyltransferase-2 (ACAT-2) expression and total ACAT activity, both of which may contribute to the observed lipid disorders (15, 35).

Secondary hyperparathyroidism is a common complication of CRF. In this study, subtotal nephrectomy markedly raised plasma PTH and phosphate concentrations in the NTX group, whereas high-calcium intake effectively lowered plasma PTH and phosphate levels, as expected. Plasma levels of 1,25(OH)2D3 were slightly but significantly reduced by NTX but were not affected by increased calcium intake. The main regulators of 1,25(OH)2D3 synthesis by 1α-hydroxylase in the kidney are phosphate, PTH, calcium, and 1,25(OH)2D3 itself (5). Modulation of phosphate concentration within the normal range can alter serum 1,25(OH)2D3: high level of phosphate inhibits and low level stimulates the synthesis. In addition, high PTH concentration increases, whereas hypercalcemia decreases active vitamin D production. 1,25(OH)2D3 also regulates its own synthesis by a negative feedback mechanism (5, 28). In this study, the long-term changes in plasma phosphate, PTH, and calcium provide an explanation why active vitamin D levels were not affected by increased calcium intake in NTX or Sham rats (5, 28).

In previous studies, a high level of LDL cholesterol has been shown to inhibit endothelium-dependent vasodilatation in both humans (25) and rats (18). LDL can impair the vascular production of NO (25) or increase the generation of superoxide anion, which reacts with NO to form peroxynitrate, which in turn may play a significant role in oxidative tissue damage (20, 36).

To examine endothelial function, we compared the ACh-induced relaxations between the study groups. The relaxations to ACh in the resistance arteries were clearly impaired in the NTX rats but were normalized by concomitant high-calcium diet. In subsequent analyses, we observed scattering of data points in separate subgroups when the plasma levels of total cholesterol, LDL-cholesterol, HDL/LDL cholesterol ratio, ionized calcium, phosphate, and PTH were depicted in relation to the sensitivity of resistance arteries to endothelium-mediated relaxation in the nephrectomized rats. Importantly, the variables reflecting renal function did not differ in the NTX and NTX-Calcium groups.

The detrimental effect of high plasma cholesterol (29), and also the beneficial effect of elevated HDL, on endothelium-dependent vasodilatation are well known.

Fig. 4. Scatterplots depicting the laboratory results in relation to the sensitivity of resistance arteries to endothelium-dependent vasorelaxation in NTX and NTX-Calcium groups. pD2, Negative logarithm. A: cholesterol; B: LDL; C: HDL-to-LDL ratio; D: ionized calcium; E: phosphate; F: PTH.
from previous studies (20). In addition, HDL is an important antioxidant, which may improve the bioavailability of NO by decreasing the formation of superoxide anion and thus oppose the negative effect of LDL in the vasculature (20, 25). Moreover, oxidative stress is a known feature of CRF, which has been evidenced by the elevation of lipid peroxidation products, depression of antioxidant capacity and impairment of antioxidant enzyme activity in both human and experimental forms of CRF (36). In the present study, the plasma level of HDL cholesterol was increased in the NTX group but so were the levels of total and LDL cholesterol. In addition, a significant reduction in HDL/LDL ratio was observed, whereby this model of renal failure was associated with clear unfavorable changes in plasma lipid profile. All of these changes were reversed by increased calcium intake, which also induced a slight elevation in the HDL/total cholesterol ratio when compared with the Sham group. Therefore, improved plasma lipid profile may play an important role in the modulation of vascular function after increased calcium intake in CRF.

Because the high-calcium diet suppressed plasma phosphate and PTH in the NTX rats, these changes may also explain the observed improvement of endothelium-mediated vasodilator properties in the resistance artery. Previous studies (11, 26, 28) suggest that secondary hyperparathyroidism and hyperphosphatemia both contribute to vascular pathology in CRF. PTH excess increases cytoplasmic Ca\(^{2+}\) and alters the production of endothelium-derived vasoactive substances (26, 27). Elevated phosphate may directly influence the metabolism of vascular smooth muscle and induce phenotypic changes in smooth muscle cells that predispose the vessel wall to calcification (12). We found that increased calcium intake actually reduced signs of calcification in aortic cross sections of NTX rats. This underlying mechanism of the reduction of vascular calcification by increased calcium intake is a subject for future studies, but a very probable explanation is the effective suppression of plasma phosphate in the NTX rats by the high-calcium diet. Altogether, the present results suggest that alterations in the calcium-phosphate balance may significantly contribute to both morphological vascular changes and impairment of vasodilatation during reduced kidney function.

Earlier studies (22, 31) have demonstrated the detrimental effect of hypertension on the endothelium-dependent and -independent relaxations of the resistance arteries. The previous findings concerning the development of hypertension in rats with renal failure are inconsistent and depend on the rat strain and the renal ablation procedure (3, 8, 13, 32). Recently, reduction of functioning renal tissue by infarction, i.e., ligation of renal arteries, was shown to increase blood pressure (measured by a telemetric method) in rats, whereas surgical excision of an equal amount of renal parenchyma did not result in the development of hypertension during the 6-wk follow up (9). In the present investigation, renal failure was associated with a small (10 mmHg) increase in blood pressure during the 12-wk follow up. This modest elevation of blood pressure in the NTX rats suggests that the observed functional alterations of the resistance arteries potentially resulted from the metabolic alterations induced by CRF and not exclusively from increased blood pressure. Nevertheless, the beneficial effects of increased calcium intake on arterial tone could not be explained by reduction of blood pressure. It is of course possible that the tail plethysmography method employed in the present study failed to detect slight changes in blood pressure.

In conclusion, CRF in rats was associated with deteriorated plasma lipid profile, secondary hyperparathyroidism, and impaired endothelium-dependent vasorelaxation of the resistance arteries. Increased calcium intake improved the lipid profile, lowered plasma PTH and phosphate, and normalized the deficient resistance artery relaxation in experimental renal failure. The improved vasorelaxation after a high-calcium diet could thus be due to reduced plasma total cholesterol and ameliorated HDL/LDL ratio, but the decreased plasma phosphate and PTH levels may also play a significant role in the vascular effects of increased calcium intake.

DISCLOSURES

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