The effect of high salt and high protein intake on calcium metabolism, bone composition and bone resorption in the rat

Annette Creedon and Kevin D. Cashman*

Department of Nutrition, University College, Cork, Ireland

(Received 6 August 1999 – Revised 10 November 1999 – Accepted 9 December 1999)

The effects of salt (NaCl) supplementation of rat diets (50 g/kg diet), with normal (200 g/kg) or high (500 g/kg) dietary casein content, were studied in 3-week-old male rats over a 3-week period. Weight gain was reduced by dietary salt but was unaffected by dietary casein. Salt-supplemented rats exhibited a two-and three-fold increase in urinary Mg and Ca excretion respectively, irrespective of dietary casein content. Dietary casein had no effect on urinary Ca or Mg. Salt reduced femoral mass but not femoral mass expressed relative to body weight, but neither variable was affected by dietary casein. Femoral Mg and P contents and concentrations were unaffected by dietary salt or casein. While femoral Ca concentration was unaffected by dietary salt, the Ca content was reduced by salt supplementation, irrespective of dietary casein content. Neither the content nor concentration of Ca in femora was affected by dietary casein. Urinary pyridinoline and deoxypyridinoline levels were increased by salt supplementation, irrespective of dietary casein content, but were unaffected by casein. Net Ca absorption was unaffected by dietary salt or casein. In conclusion, these results show that salt supplementation over the short-term increased the rate of bone resorption in rats. This was as a consequence of Na-induced calciuria. On the other hand, a high dietary protein intake had no effect on Ca metabolism, bone composition or bone resorption, nor did it augment the Na-induced calciuria or increased rate of bone resorption.

Salt: Protein: Calcium: Rat bone

There is evidence that high dietary Na and protein intakes may have adverse effects on bone metabolism and may be risk factors for osteoporosis. Increasing Na intake is associated with increased urinary Ca loss (calciuria) in experimental animals (Goulding & Campbell, 1984; Whiting & Cole, 1986; Greger et al. 1987; Shortt & Flynn, 1991; Chan & Swaminathan, 1994) and man (Shortt et al. 1988; Shortt & Flynn, 1990; Itoh & Suyama, 1996; Leitz et al. 1997; Ginty et al. 1998). This dependence of urinary Ca excretion on urinary Na excretion has been attributed to the existence of linked or common reabsorption pathways for both ions in the convoluted portion of the proximal tubule and thick ascending loop of Henle (Shortt & Flynn, 1990).

A calciuric effect is also seen with high-protein diets (in human subjects: Allen et al. 1979a,b; Hegsted, 1981; Mahalko et al. 1983; Kerstetter et al. 1997; Pannemans et al. 1997; in rats: Allen & Hall, 1978; Whiting & Draper, 1980; Howe & Beecher, 1981; Chan & Swaminathan, 1994). However, in this case, the calciuria has been attributed to an increased glomerular filtration rate and a decreased tubular Ca reabsorption caused by catabolism of S-containing amino acids native to the protein (Kim & Linkswiler, 1979; Schuette et al. 1980). It has been estimated that a doubling of dietary protein intake increases urinary Ca by approximately 50% (Walker & Linkswiler, 1972; Heaney, 1993). Furthermore, there is some evidence that the calciuric effects of high Na and high protein intakes may be additive (Goulding & Campbell, 1984; Chan & Swaminathan, 1994). However, it is not known to what extent Na- (and/or protein-) induced calciuria is compensated for by increased absorption of dietary Ca and/or reduced endogenous Ca losses or to what extent this Ca is derived from resorption of bone (Shortt & Flynn, 1990; Itoh et al. 1998).

There is evidence that very high Na intakes adversely affects Ca homeostasis and reduces bone mass and bone Ca content in rats (for reviews see Shortt & Flynn, 1990; Massey & Whiting, 1996). There is also evidence that urinary hydroxyproline, a marker of bone resorption, is increased with increasing Na intake in man (Goulding, 1981; Goulding & Lim, 1993; Nordin & Polley, 1987; McParland et al. 1989; Need et al. 1991; Itoh & Suyama, 1996) and animals (Goulding & Campbell, 1983; Goulding & Gold, 1986, 1988; Chan et al. 1993; Chan & Swaminathan, 1994, 1998). Likewise, increasing dietary protein intake is associated

Abbreviations: Dpyr, deoxypyridinoline; PTH, parathyroid hormone; Pyr, pyridinoline.

* Corresponding author: Dr Kevin D. Cashman, fax +353 21 270244, email k.cashman@ucc.ie
with increased urinary excretion of hydroxyproline in human subjects (Schuette et al. 1981) and rats (Goulding & Campbell, 1984; Chan & Swaminathan, 1994). Chan & Swaminathan (1994) examined the effect of feeding a diet high in protein and salt for 4 months on the urinary excretion of hydroxyproline in rats. They found significant effects of dietary protein and dietary salt on hydroxyproline excretion, but no interaction between the two dietary factors. However, urinary hydroxyproline has been shown to lack sensitivity and specificity as an indicator of bone resorption and urinary pyridinium crosslinks of collagen are considered to be more reliable biochemical markers of bone resorption in human subjects (Delmas, 1992; Ginty et al. 1998; Cashman & Flynn, 1999) and rats (Black et al. 1989; Egget et al. 1994). To date, there has been no study of the effect of high dietary Na and protein intake on the rate of bone resorption in human subjects or rats, as assessed by these more specific and sensitive urinary markers.

Thus, the aim of the present study was to investigate the effect of a high-Na, high-protein diet on Ca metabolism, bone composition and the urinary pyridinium crosslinks of collagen in rats.

Materials and methods

Preparation of rat diets

The AIN-76 purified diet (that recommended for rats by the American Institute of Nutrition, 1977) was used in the present study (Table 1).

Experimental design

Thirty-two male rats, 3 weeks old, Wistar strain (average weight 57 g), obtained from the Biological Services Unit, University College, Cork, were randomized by weight into four groups of eight rats each. One group was fed ad libitum on a semipurified basal diet (AIN-76) as outlined in Table 1 while a second group was fed a diet (high-protein) similar to the basal diet in every respect except that 300 g/kg of the sucrose component was replaced by dietary caseine. The third and fourth groups were fed ad libitum on the basal and high-protein diets supplemented with NaCl (50 g/kg diet; high-salt and high-protein–high-salt diets respectively). Rats were housed individually and feed was provided at 17.00 hours each day. All animals were given distilled water ad libitum for the duration of the study. Rats were weighed weekly and examined daily for general condition. During the last week of the study, all rats were placed in individual metabolism cages with a grid-floor and a facility for separate collection of faeces and urine. To acclimate the animals to the new environment, rats were placed in these cages 2 d before the beginning of a 4 d metabolic period for determination of net dietary Ca absorption and urinary pyridinium crosslink excretion. Ad libitum intake of AIN-76 diets was measured during a 2 d period to determine average food intake per group. To assure complete and equivalent consumption of all food offered during the 4 d metabolic period, an equalized feeding paradigm was used. In the present study, the amount of food offered to all rats during the 4 d balance period was limited to 90% of the ad libitum food intake of the group that ate the least amount of food during the previous 2 d. Feed was provided at 09.00 hours every day over the period and any remaining feed at 09.00 hours the following day was weighed. Quantitative collections of faeces were made over the 4 d period and these were pooled for each rat and stored at 4°C until required for analysis.

Urine samples (24 h) were also collected for each animal during the metabolic period in vessels covered with Al foil to prevent degradation by light of the pyridinium crosslinks. The urine samples for each animal were pooled and the volumes recorded. Portions of the pooled urine samples were acidified with 12 M HCl (225 μl/100 ml urine) and stored at −20°C until required for analysis.

Net Ca absorption (%) was calculated as the difference between Ca intake from the diet and Ca recovered in the faeces during the 4 d period, while Ca retention was calculated as the difference between dietary Ca intake and Ca excretion in faeces and urine.

After 21 d on the respective diets, all animals were killed by over-exposure to diethyl ether and final body weights were recorded. Femora were harvested, cleaned of adhering soft tissue, dried overnight at 110°C, weighed and stored in sealed containers until required for mineral analysis.

Experimental technique

Urinary pyridinoline and deoxypyridinoline. Pooled urine samples for each animal were analysed in duplicate using a three-step procedure. Urine was first hydrolysed with an equal volume of 12 M-HCl at 110°C for 18 h, the crosslinks

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### Table 1. Composition of the AIN-76 basal diet (American Institute of Nutrition, 1977)

<table>
<thead>
<tr>
<th>Ingredient*</th>
<th>Content (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casein</td>
<td>200.0†</td>
</tr>
<tr>
<td>DL-Methionine</td>
<td>3.0</td>
</tr>
<tr>
<td>Maize starch</td>
<td>150.0</td>
</tr>
<tr>
<td>Sucrose</td>
<td>484.9</td>
</tr>
<tr>
<td>Fibre</td>
<td>50.0</td>
</tr>
<tr>
<td>NaCl</td>
<td>2.6†</td>
</tr>
<tr>
<td>Maize oil</td>
<td>50.0</td>
</tr>
<tr>
<td>AIN mineral mix‡</td>
<td>35.0</td>
</tr>
<tr>
<td>AIN vitamin mix§</td>
<td>10.0</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>12.5</td>
</tr>
<tr>
<td>Choline bitartrate</td>
<td>2.0</td>
</tr>
</tbody>
</table>

* Sources of ingredients: casein (sodium caseinate, Kerrymore Milk Products Ltd., Listowel, Co. Kerry, Ireland); DL-methionine (Rhone Poulenc, Animal Nutrition, Commeny, France); maize starch (Cagill Bergen op Zoom, The Netherlands); sucrose (Irish Sugar plc, Sugar Division, Athy Road, Carlow, Ireland); fibre (Avicel microcrystalline cellulose, N.F., FMC International Food and Pharmaceutical Products Division, Little Island, Cork, Ireland); maize oil (St Bernard’s brand, Dunnes Stores Ltd, 67 Stephen Street, Upper Dublin 8, Ireland); choline bitartrate (Brown and Gilmore, Carrigaline East, Co. Cork, Ireland).

† Representing diets containing (per kg): 200 and 2.6 g casein and salt respectively (basal diet); level of addition of protein and/or salt was increased appropriately (in replacement of sucrose) for the high-protein, high-salt and high-protein–high-salt diets.

‡ Contained (g/kg): potassium dihydrogen phosphate 376, dipotassium hydrogen phosphate 160, magnesium oxide 24, manganous carbonate 3.5, ferric citrate 6, zinc carbonate 1.6, cupric carbonate 0.3, potassium iodate 0.01, sodium selenite 0.01, chromium potassium sulphate 0.55, sucrose 428.

§ Contained (g/kg): nicotinic acid 3.0, calcium pantothenate 1.6, riboflavin 600 mg, thiamin-HCl 600 mg, pyridoxine-HCl 700 mg, pteroylmonoglutamic acid 200 mg, biotin 20 mg, cyanocobalamin 1 mg, cholecalciferol 2.5 mg, menaquinone 5 mg, retinyl palmitate 120 mg, DL-α tocopheryl acetate 5000 mg.
were then extracted by CF1 cellulose chromatography with the use of an internal standard (acetylated pyridinoline (Pyr), MetraBioSystems Ltd, Wheatley, Oxon., UK) and were measured using a reversed-phase HPLC method with fluorescence detection (Colwell et al. 1993). The acetylated Pyr was used in accordance with the method as described by Calabresi et al. (1994) and Robins et al. (1994). The crosslinks contents of urines were quantitated by external stan-

dardization using a commercially available Pyr–deoxopyridinoline (Dpyr) HPLC calibrator (MetraBioSystems Ltd). The intra-assay CV for Pyr and Dpyr measured as the variation between ten chromatograms obtained between column regenerations as described by Colwell et al. (1993) were 6 % and 9 % respectively. The inter-assay CV for Pyr and Dpyr were 7 and 8 % respectively.

Femoral phosphorus and femoral and urinary calcium and magnesium levels. Weighed femora (dried) were digested in 10 ml 16 M\(\text{HNO}_3\)-12 M\(\text{HClO}_4\) (2:1, v/v) on a hot plate (S & J Juniper & Co., Essex, UK) until the sample colour resembled that of the reagent blank. Ca and Mg were analysed in duplicate in femoral digests and urine by atomic absorption spectrophotometry (Pye-Unicam Atomic Absorption Spectrophotometer, Model SP9; Cambridge, Camb., UK) after appropriate dilution with LaCl\(_3\) solution (5 g/l, BDH Ltd, Poole, Dorset, UK). A range of Ca and Mg standards were used to obtain Ca and Mg calibration curves. The intra- and inter-assay CV for Ca were 2.8 % and 7.8 %, and for Mg were 3.2 % and 8.8 % respectively. P was determined in the femoral digests by the method of Weissman & Pileggi (1974). The intra- and inter-assay CV for P were 4.2 % and 6.1 % respectively.

Feed and faecal calcium levels. Pooled faecal samples (4 d) from each animal were dried overnight at 110°C and mixed thoroughly. Aliquots of the dried faecal samples and of the AIN-76 diets were digested in 10 ml of 16 M\(\text{HNO}_3\)-12 M\(\text{HClO}_4\) (2:1, v/v) on a hot plate (S & J Juniper & Co.) until the sample colour resembled that of the reagent blank. Ca was analysed in duplicate in faecal and feed digests by atomic absorption spectrophotometry (Pye-Unicam Atomic Absorption Spectrophotometer) after appropriate dilution with LaCl\(_3\) solution (5 g/l, BDH Ltd). A range of Ca standards was used to obtain Ca calibration curves. The intra- and inter-assay CV for Ca were 2.8 % and 7.8 % respectively.

### Table 2. The effect of dietary salt and protein on weight gain, calcium absorption and retention and urinary calcium and magnesium in young male rats

<table>
<thead>
<tr>
<th>Dietary treatment …</th>
<th>Low-salt</th>
<th>High-salt</th>
<th>Statistical significance of variance ratio (P), effects of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-casein (n 8)</td>
<td>High-casein (n 8)</td>
<td>Pooled SEM</td>
</tr>
<tr>
<td>Weight gain (g/21 d)</td>
<td>73.0</td>
<td>71.2</td>
<td>55.7 50.1 4.0</td>
</tr>
<tr>
<td>Urinary Ca (mg/4 d)</td>
<td>1.5</td>
<td>1.6</td>
<td>4.8 5.3 0.4</td>
</tr>
<tr>
<td>Urinary Mg (mg/4 d)</td>
<td>2.4</td>
<td>2.6</td>
<td>4.5 4.8 0.2</td>
</tr>
<tr>
<td>Faecal Ca (mg)</td>
<td>101</td>
<td>97</td>
<td>100 102 4</td>
</tr>
<tr>
<td>Ca retention (mg)</td>
<td>242</td>
<td>232</td>
<td>239 235 4</td>
</tr>
<tr>
<td>Net Ca absorption:† (mg)</td>
<td>244 233</td>
<td>243 240 3</td>
<td></td>
</tr>
<tr>
<td>(% )</td>
<td>70.7</td>
<td>71.6</td>
<td>70.9 70.3 1.1</td>
</tr>
</tbody>
</table>

*For details of diets and procedures, see Table 1 and pp. 50–51.
†Calculated of the last 4 d of the 3-week study period.

### Discussion

The results of the present study indicate that short-term intakes of salt supplements (50 g/kg diet) significantly increased urinary Ca and Mg excretion in rats irrespective of the protein (casein) content of the diet. The effect of salt...
on urinary mineral excretion was most marked in the case of Ca, with a three-fold increase in animals given salt-supplemented compared with non-supplemented diets. These findings are consistent with the results of previous studies (Goulding & Campbell, 1984; Goulding & Gold, 1986; Shortt & Flynn, 1991; Chan & Swaminathan, 1994). The dependence of urinary Ca excretion on urinary Na excretion has been attributed to the existence of linked or common reabsorption pathways for the ions in the convoluted portion of the proximal tubule and in the loop of Henle (Shortt & Flynn, 1990, 1991).

In the present study, increasing the content of dietary protein (casein) in the diet had no effect on urinary Na or Mg excretion. Previous reports have indicated that dietary protein increases the urinary excretion of Ca in rats (Bell et al. 1975; Allen & Hall, 1978; Whiting & Draper, 1980; Howe & Beecher, 1981; Goulding & Campbell, 1984; Chan & Swaminathan, 1994). However, the magnitude and duration of this hypercalciuria have varied significantly among studies. For example, 8-month-old male rats, Sprague-Dawley strain, fed 400 g protein/kg diet, as a mixture of gelatin, lactalbumin and casein, exhibited a 10-fold increase in urinary Ca, lasting at least 100 d, relative to controls fed 100 g casein/kg (Bell et al. 1975). In contrast, 28-d-old male rats, Wistar strain, fed 360 g casein/kg diet have been reported to exhibit only a slight calcium which disappeared by 28 d, relative to controls fed 180 g casein/kg diet (Allen & Hall, 1978). Casein is a phosphorylated protein and, as such, increasing its level of inclusion in the diet in the present study from 200 to 500 g/kg would have raised the P content of the diet by about 2 g P/kg diet (Brommage et al. 1991). Since dietary P reduces urinary Ca excretion (Anderson & Draper, 1972; Howe & Beecher, 1981), this might explain, at least in part, why the increased casein content in the diet did not increase urinary Ca levels. However, Goulding & Campbell (1984) found that young growing male albino rats fed a high-casein diet (600 g casein/kg diet) excreted significantly more Ca in urine than rats fed a moderate-casein diet (250 g casein/kg diet) over a 14 d period. Whiting & Draper (1980) suggest that the degree of hypercalciuria seen with high-protein feeding in the rat depends on the length of time the diet is fed and on the type and level of protein used. Kerstetter & Allen (1994) on reviewing this topic concluded that while the acute response of rats to a high-protein diet appears to be similar to that of human subjects, the hypercalciuretic response disappears with time. On the other hand, the calciuretic response of human subjects to dietary protein does not diminish with time (Kerstetter & Allen, 1994).

In the present study, salt supplementation increased the excretion of pyridinium crosslinks of collagen in urine, suggesting that the rate of bone resorption was increased. This is the first study to our knowledge that has examined the effect of increased Na and/or protein intake on urinary pyridinium crosslink excretion in the rat. Three recent studies have investigated the effects of dietary Na on urinary pyridinium crosslinks of collagen in human subjects. Evans et al. (1997) reported that urinary Dpyr in postmenopausal women was increased by a high Na intake, while Lietz et al. (1997) found no effect. With regard to premenopausal women, both Evans et al. (1997) and Ginty et al. (1998) reported that urinary Dpyr was unaffected by dietary Na intake. Earlier studies in human subjects and experimental rats have reported that higher Na intakes are associated with increased urinary excretion of hydroxyproline (in man: Goulding & Lim, 1983; Goulding et al. 1986; Goulding & MacDonald, 1986; Chan et al. 1992; Itoh & Suyama, 1996; in rats: Goulding & Campbell, 1983; Goulding & Gold, 1986, 1988; Chan & Swaminathan, 1994). However, the suitability of urinary hydroxyproline as a marker of bone resorption has been questioned due to its lack of specificity and sensitivity and the changes in hydroxyproline excretion may not necessarily reflect changes in bone metabolism, but rather may be due to contributions from other sources, e.g. connective tissues or from an alteration in the liver catabolism of hydroxyproline (Lietz et al. 1997). Additionally, in a number of these studies, dietary hydroxyproline was not controlled and it has been well established that dietary

| Table 3. The effect of dietary salt and protein on urinary pyridinoline (Pyr) and deoxypyridinoline (Dpyr) concentrations and on femur dry weight and concentrations of calcium, magnesium and phosphorus in young male rats* |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Dietary treatment** | **Low-salt** | **High-salt** | **Statistical significance of variance ratio (P), effects of:** | **Low-casein** | **High-casein** | **Pooled SEM** |
| | (n 8) | (n 8) | | (n 8) | (n 8) | |
| **Femur** | | | | | | |
| Dry wt: | | | | | | |
| (mg) | 192 | 198 | 153 | 171 | 4.2 | 0.038 |
| (g/kg body wt) | 1.46 | 1.52 | 1.46 | 1.48 | 0.05 | – |
| Ca (mg/bone) | 37.2 | 35.5 | 32.0 | 29.8 | 1.9 | 0.017 |
| Mg (mg/bone) | 0.71 | 0.69 | 0.67 | 0.69 | 0.04 | – |
| P (mg/bone) | 21.4 | 19.3 | 18.0 | 22.5 | 1.9 | – |
| Ca (mg/g dry wt) | 196 | 197 | 188 | 182 | 5 | – |
| Mg (mg/g dry wt) | 3.99 | 3.86 | 3.58 | 3.62 | 0.22 | – |
| P (mg/g dry wt) | 112 | 116 | 105 | 118 | 5 | – |
| **Urine** | | | | | | |
| Pyr (nmol/d) | 10.8 | 9.7 | 12.4 | 13.4 | 0.7 | 0.008 |
| Dpyr (nmol/d) | 9.6 | 9.5 | 12.0 | 12.4 | 0.6 | 0.006 |

* For details of diets and procedures, see Table 1 and pp. 50–51.
Dietary salt, protein and rat bone

hydroxyproline may affect urinary hydroxyproline excretion (Kivirikko, 1970; Massey & Whiting, 1996).

The impact of dietary protein on bone resorption is controversial. In the present study, increasing the casein content of the diet had no effect on the urinary excretion of pyridinium crosslinks of collagen. This is in agreement with the findings of Shapses et al. (1995) in human subjects who reported that increasing the levels of dietary protein had no effect on bone resorption in young adult subjects, as measured by the pyridinium crosslinks levels in urine. More recently, Kerstetter et al. (1999) found that while switching healthy young adult women from a low (45 g/d) to a medium dietary protein intake (63 g/d) increased the urinary excretion of N-telopeptides, another sensitive and specific marker of bone resorption, changing from the medium to a high level of protein intake (129 g/d) had no effect. On the other hand, Schuette et al. (1981) and both Goulding & Campbell (1984) and Chan & Swaminathan (1994) reported that urinary hydroxyproline excretion increased with increasing levels of dietary protein intake in humans and rats respectively. However, as pointed out above, the suitability of urinary hydroxyproline as a marker of bone resorption has been questioned. The lack of effect of high dietary protein intakes on the rate of bone resorption (as measured by the more specific and sensitive biomarkers) relative to medium, or recommended, levels may be due to the fact that, despite causing calcitriol, protein loads appear not to elevate circulating parathyroid hormone (PTH) levels, a potent stimulator of bone resorption (Adams et al. 1979; Kim & Linkswiler, 1979; Kerstetter et al. 1997).

In the present study, femoral mass was reduced by salt supplementation but was unaffected by dietary casein. However, when expressed on a body weight basis, there was no effect of salt on femoral mass, suggesting that the effect of salt was due, at least in part, to lower body weight gain in salt-supplemented animals. Shortt & Flynn (1991) have reported similar effects of salt supplementation on tibia mass in rats. Femoral Ca, but not P or Mg, content was reduced by dietary salt. However, salt had no effect on femoral Ca, Mg or P concentration. Therefore, in spite of the hypercalcemia and increased rate of bone resorption in salt-supplemented rats, their bone mass, when adjusted for body weight, was unaffected. This is in agreement with the findings of other studies in rats that found that salt supplementation (80 g/kg diet) for 10 d–8 weeks had no effect on bone mass despite the presence of hypercalcemia and increased bone resorption, as measured by urinary hydroxyproline (Goulding & Gold, 1988; Chan et al. 1993). Thus, it may be that, as suggested by Goulding & Gold (1988), the duration of the present study was too short to elicit significant osteopenia. There is, for example, considerable evidence that salt supplementation (80 g/kg diet) for longer periods (2–4 months) reduces bone mass and Ca content in young and adult rats consuming diets either deficient (Goulding & Campbell, 1982, 1983; Goulding & Gold, 1986; Chan et al. 1993) or adequate (Goulding & Campbell, 1984; Chan et al. 1993; Chan & Swaminathan, 1994, 1998) in Ca, although some studies have failed to show this (Goulding, 1980). In addition, Chan et al. (1993) and Chan & Swaminathan (1998) found that chronic (i.e. 12 months) high Na intake reduced bone mineral content in rats consuming diets adequate in Ca. Alternatively, the lack of effect of salt supplementation on femur mass in the present study, in spite of the evident hypercalcemia and increased bone resorption, may have been due to Ca mobilization from some part of the skeleton other than the femur. The lack of effect of dietary casein on bone mass or macro-mineral composition in the present study is in agreement with several studies in rats which failed to find an effect of excess dietary protein on these variables (Allen & Hall, 1978; Whiting & Draper, 1981; Goulding & Campbell, 1984).

It has been suggested that Na-induced hypercalcemia leads to a reduction in serum ionized-Ca which, in turn, stimulates the secretion of PTH (Goulding et al. 1986). PTH helps to restore serum ionized-Ca by increasing bone resorption and/or, via increased 1,25 dihydroxy-vitamin D$_3$, increasing intestinal absorption of Ca (Shortt & Flynn, 1990). Increased Ca absorption would normalize plasma Ca which, in turn, would reduce the stimulus for PTH secretion and for PTH-stimulated bone resorption. In the present study, however, despite the marked increase in urinary Ca loss, salt supplementation did not increase net Ca absorption. This finding is in agreement with those of similar studies in rats fed on diets deficient (Goulding & Campbell, 1983; Goulding & McIntosh, 1986) or adequate (Goulding & Campbell, 1984; Shortt & Flynn, 1991) in Ca which showed that salt supplementation (80 g/kg diet) did not increase net Ca absorption. In contrast, Goulding & Gold (1986) reported increased net Ca absorption in salt-supplemented rats fed on a Ca-deficient diet for 12 weeks.

In the present study, salt supplementation increased urinary Ca excretion by an amount equivalent to only about 2 % of the total Ca absorbed and retained. While the precision of the balance method does not permit determination of whether Ca absorption or retention were altered by such an amount, it is clear from the elevated urinary pyridinium crosslinks levels and lower femoral Ca content of the animals given salt-supplemented diets that homeostasis was achieved, at least in part, at the expense of bone Ca.

There is some evidence in human subjects to suggest that healthy individuals respond to Na-induced calcitriol by a PTH-mediated increase in intestinal Ca absorption (Meyer et al. 1976; Breslau et al. 1982), although Evans et al. (1997) did not observe any effect of increasing dietary Na on Sr absorption (an index of Ca absorption) in premenopausal women. However, this adaptive mechanism does not appear to function in all individuals, e.g. those with impaired parathyroid function (Breslau et al. 1989); even in those individuals who appear to adapt, the increase in net Ca absorption may not be sufficient to offset the increase in urinary Ca losses (Breslau et al. 1982). In addition, the capacity for such adaptation may be limited by low dietary Ca intakes, poor vitamin D status, impaired renal function or poor intestinal Ca absorption (Shortt & Flynn, 1990).

In the present study, dietary protein (casein) had no effect on net Ca absorption. This is in agreement with several studies in rats (Allen & Hall, 1978; Howe & Beecher, 1981; Yuan & Kitts, 1994) and human subjects (Spencer et al. 1978; Heaney & Recker, 1982; Schuette & Linkswiler, 1982; Spencer et al. 1983; Draper et al. 1991) which have failed
to find an effect of high dietary protein intake on Ca absorption.

In conclusion, the salt-induced increase in the rate of bone resorption in rats, as assessed by the urinary pyridinium crosslinks, observed in the present study confirms the findings of previous studies which used urinary hydroxyproline as a marker of bone resorption. This increased rate of bone resorption was as a consequence of Na-induced calciuria. On the other hand, a high dietary protein intake had no effect on Ca metabolism, bone composition or bone resorption. Nor did it augment the Na-induced calciuria or increased rate of bone resorption. However, due to differences in the calciuric response to dietary protein between rats and human subjects, together with evidence from epidemiological studies which show a strong positive correlation between animal protein intake and incidence of fracture of the femoral neck (Feskanich et al. 1996; Meyer et al. 1997), there is a need for further study of the effect of high protein intake, independently and in combination with high salt intake, on bone metabolism in human subjects.

Acknowledgement

This research has been part-funded by grant aid under the Food Sub-Programme of the Operational Programme for Industrial Development which is administered by the Department of Agriculture and Food, Dublin, and supported by national and European Union funds.

References

Adams ND, Gray RW & Lemann J (1979) The calciuria of increased fixed acid production in humans: evidence against a role for parathyroid hormone and 1,25 (OH)2-vitamin D. Calcified Tissue International 28, 233–238.


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