The effect of a high-protein, high-sodium diet on calcium and bone metabolism in postmenopausal women and its interaction with vitamin D receptor genotype

Mary Harrington¹, Teresa Bennett¹, Jette Jakobsen³, Lars Ovesen³, Christine Brot³, Albert Flynn¹ and Kevin D. Cashman¹,²*

¹Department of Food and Nutritional Sciences, Cork, Republic of Ireland
²Department of Medicine, University College, Cork, Republic of Ireland
³Institute of Food Safety and Nutrition, Danish Veterinary and Food Administration, Soborg, Denmark

(Received 15 May 2003 – Revised 19 August 2003 – Accepted 9 September 2003)

The influence of a high-Na, high-protein (calciuric) diet on Ca and bone metabolism was investigated in postmenopausal women (aged 50–67 years) who were stratified by vitamin D receptor (VDR) genotype. In a crossover trial, twenty-four women were randomly assigned to a diet high in protein (90 g/d) and Na (180 mmol/d) or a diet adequate in protein (70 g/d) and low in Na (65 mmol/d) for 4 weeks, followed by crossover to the alternative dietary regimen for a further 4 weeks. Dietary Ca intake was maintained at usual intakes (about 20 mmol (800 mg)/d). Urinary Na, K, Ca, N and type I collagen cross-linked N-telopeptide (NTx; a marker of bone resorption), plasma parathyroid hormone (PTH), serum 25-hydroxycholecalciferol (25(OH)D³), 1,25-dihydroxycholecalciferol (1,25(OH)₂D³), osteocalcin and bone-specific alkaline phosphatase (B-Alkphase) were measured in 24 h urine samples and fasting blood samples collected at the end of each dietary period. The calciuric diet significantly (P<0.05) increased mean urinary Na, K, Ca and NTx (by 19%) compared with the basal diet, but had no effect on circulating 25(OH)D³, 1,25(OH)₂D³, PTH, osteocalcin or B-Alkphase in the total group (n 24). There were no differences in serum markers or urinary minerals between the basal and calciuric diet in either VDR genotype groups. While the calciuric diet significantly increased urinary NTx (by 25·6 %, P<0·01) in the f + VDR group (n 10; carrying one or more (f) Fok I alleles), it had no effect in the f – VDR group (n 14; not carrying any Fok I alleles). It is concluded that the Na- and protein-induced urinary Ca loss is compensated for by increased bone resorption and that this response may be influenced by VDR genotype.

Sodium: Protein: Bone metabolism: Vitamin D receptor: Postmenopausal women

Various dietary factors have been suggested as risk factors for osteoporosis, including high protein and high salt intakes (Cohen & Roe, 2000). Increasing Na intake within the usual dietary range is associated with increased urinary Ca loss (calciuria) (Shortt et al. 1988; Itoh & Suyama, 1996; Ginty et al. 1998b; Sellmeyer et al. 2002; for reviews, see Shortt & Flynn, 1990; Massey & Whiting, 1996). It has been estimated that a 100 mmol increment in daily Na intake is associated with an average additional loss of urinary Ca of approximately 1 mmol in free-living normocalciuric healthy populations (Nordin et al. 1993). A calciuric effect is also associated with high-protein diets (Allen et al. 1979a,b; Schuette et al. 1980; Hegsted et al. 1981; Mahalko et al. 1983; Pannemans et al. 1997; for review, see Kerstetter & Allen, 1994). It has been estimated that a doubling of dietary protein intake increases daily urinary Ca excretion by approximately 50 % (Walker & Linkswwiler, 1972; Heaney, 1993). Furthermore, there is some evidence from animal studies 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 urinary Ca is derived from resorption of bone (Shortt & Flynn, 1990; Itoh et al. 1998).

There is evidence that increasing intakes of both Na and protein significantly increases urinary-based biochemical markers of bone resorption, and this has been associated with increased risk of hip fracture (Garnero et al. 1996, 2000). For example, Sellmeyer et al. (2002) recently reported that when postmenopausal women, adapted to a low-Na diet (87 mmol/d) for 3 weeks, were switched to a high-Na diet (225 mmol/d) diet for a further 4 weeks, urinary type I collagen cross-linked N-telopeptide (NTx) levels

Abbreviations: Dpyr, deoxypyridinoline; NTx, type I collagen cross-linked N-telopeptide; PTH, parathyroid hormone; 1,25(OH)₂D³, 1,25-dihydroxycholecalciferol; 25(OH)D³, 25-hydroxycholecalciferol.

* Corresponding author: Professor Kevin D. Cashman, fax +353 21 4270244, email k.cashman@ucc.ie
were significantly increased. Similarly, Evans et al. (1997) reported that urinary excretion of deoxypyridinoline (Dpyr) was greater following 7 days on a high-Na diet (300 mmol/d) than a low-Na diet (50 mmol/d) for postmenopausal but not premenopausal women. Shortt & Flynn (1990) have suggested that postmenopausal women are a group whose adaptive mechanisms for increasing Ca absorption in response to Na-induced calciauria may be incomplete, and thus the Ca needed to buffer the additional loss in urine may be derived from bone resorption. However, Lietz et al. (1997) found no effect of increasing Na intake for 8 days on urinary Dpyr levels in postmenopausal women.

Increasing dietary protein is associated with increased urinary hydroxyproline (Schuette et al. 1981; Schuette & Linkswiler, 1982) and NTx excretion (Kerstetter et al. 1999) in young adult men and women respectively. However, Shaples et al. (1995) found no effect of increasing dietary protein on urinary Dpyr excretion in young adults. The effect of a high protein intake on bone turnover in postmenopausal women has not been reported. Furthermore, to date there has been no study of the effect of high dietary Na in combination with high protein intake on urinary Ca excretion and biomarkers of Ca and bone metabolism in human subjects.

Recent evidence suggests that the increased susceptibility to bone loss associated with the vitamin D receptor (VDR) genotype in postmenopausal women may be mediated, at least in part, through processes which are diet related. For example, Rapuri et al. (2001) recently showed that genetic variation in the VDR gene interacts with high caffeine intake (another diet-derived calciuric factor) in determining the rate of bone loss in postmenopausal women.

Thus, the aims of the present study were first, to investigate the effect of a high-Na, high-protein (i.e. a calciuric) diet on urinary Ca excretion and biomarkers of Ca and bone metabolism in postmenopausal women, and second, to investigate the possible interaction between this calciuric diet and VDR genotype on the rate of bone turnover in postmenopausal women.

Table 1. Characteristics of the group of apparently healthy postmenopausal women (n 26) selected for the high-sodium, high-protein intervention trial (Mean values, standard deviations and ranges)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>57·1</td>
<td>5·1</td>
<td>50–67</td>
</tr>
<tr>
<td>Years since menopause (years)</td>
<td>6·1</td>
<td>4·8</td>
<td>2–20</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1·65</td>
<td>0·06</td>
<td>1·53–1·75</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65·3</td>
<td>11·1</td>
<td>49–86</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23·9</td>
<td>3·7</td>
<td>18·5–32·3</td>
</tr>
</tbody>
</table>

Ethical considerations

Before participation in this study, all subjects signed an informed consent document approved by the Clinical Research Ethics Committee of the Cork Teaching Hospitals.

Design

The study consisted of a randomized crossover trial of the effect of a ‘high’ Na (180 mmol/d), ‘high’ protein (90 g/d) intake (i.e. calciuric diet) v. a ‘low’ Na (65 mmol/d), ‘usual’ protein (70 g/d) intake (basal diet) for 4 weeks on the metabolism of Ca and bone in postmenopausal women. The dietary intervention trial was designed in two successive dietary periods, each of 4 weeks. Subjects were assigned randomly to the calciuric diet (i.e. high in Na and protein) or the basal diet (i.e. adequate in protein and low in Na) for 4 weeks, followed by crossover to the alternative dietary regimen for a further 4 weeks (Fig. 1). The calciuric diet was based on the basal diet (Shortt et al. 1988; Ginty et al. 1998b), to which appropriate quantities of protein and Na were added while maintaining Ca intake at usual levels (about 20 mmol (800 mg)/d). The additional Na was added through dietary means as described previously by Ginty et al. (1998b). The additional protein was in the form of protein-rich bread (see later) that also provided extra Na. As the intervention took at least 2 months to complete, subjects were supplemented throughout with 5 μg cholecalciferol/d, commencing 1 month before the first intervention, in order to avoid seasonal changes in vitamin D status. Subjects were instructed to collect consecutive 24 h urine samples for the last 2 days of each dietary period and during the week immediately preceding the trial (baseline). In addition, after an overnight fast, a blood sample (25 ml) was taken at 09.00 hours on the morning of the last day of each dietary period and during the baseline week immediately preceding the trial. Blood pressure was measured on the first day and days 7, 14, 21 and 28 of each dietary period and during the baseline week. Four-day (including weekend) estimated diet records for each subject were obtained by a trained investigator during each treatment period and during the baseline week immediately preceding the trial.

Bread preparation

A high-protein, high-Na bread was manufactured in the experimental bakery at University College, Cork, Republic...
of Ireland. The bread was made from dough of the following composition: sodium caseinate (Dairygold, Mitchelstown, Co. Cork, Republic of Ireland) 136 g; wheat gluten (Gluvital 21000; Cerestar, Eridania Beghin-Say, Germany) 136 g; spray-dried egg white powder (Sanova Foods A/S, Odense, Denmark) 30 g; salt (Saxa; RHM Foods, Glasnevin, Co. Dublin, Republic of Ireland) 18 g, stoneground coarse wholemeal flour (Odlums, Kennedy Quay, Cork, Republic of Ireland) 227 g, bakers’ flour (Odlums) 68 g, granulated sugar (Siucra; Irish Sugar plc., Co. Carlow, Republic of Ireland) 9 g, instant dry yeast (Mauripan; Burns Philip, Stillorgan, Co. Dublin, Ireland) 9 g, sunflower oil (Flora; Van Den Berg Foods Ltd, Crawley, Sussex, UK) 17 ml, dough emulsifier (sodium stearoyl 2-lactylate; Quest International Irl Ltd, Carrigaline, Co. Cork, Republic of Ireland) 1·5; water 455 ml. The high-protein, high-Na bread contained (g/kg bread): protein 244·0, Na 8·2, P 2·5, K 1·6, Ca 0·3.

A normal-protein, low-Na bread was also manufactured from dough of the following composition: stoneground coarse wholemeal flour (Odlums) 500 g; bakers’ flour (Odlums) 167 g; salt (Saxa; RHM Foods) 6 g, granulated sugar (Siucra; Irish Sugar plc.) 42 g; instant dry yeast (Mauripan) 21 g; sunflower oil (Flora; Van Den Berg Foods Ltd) 42 ml, dough emulsifier (sodium stearoyl 2-lactylate; Quest International Irl Ltd) 3·3 g; water 333 ml. The normal-protein, low-Na bread contained (g/kg bread): protein 83·0, Na 3·8, P 1·1, K 2·5, Ca 0·4.
**Blood pressure measurements**

Blood pressure (systolic and diastolic) was measured three times in succession in the seated position after the subjects sat quietly for at least 5 min in the morning, using an Omron HEM-705CP fully automatic digital blood-pressure monitor (Omron Healthcare Europe B.V., Hoofddorp, The Netherlands), which was validated by the British Hypertension Society.

**Dietary analysis**


**Collection and preparation of samples**

Subjects were supplied with suitable collection containers for urine samples and asked to make 24 h collections at baseline and for the last two consecutive days of each dietary period. The volumes of 24 h urine collections were recorded and portions of urine were acidified using 0·36 M-HCl and stored at 20°C. The intra-assay CV was 5 %.

Blood pressure (systolic and diastolic) was measured three times in succession in the seated position after the subjects sat quietly for at least 5 min in the morning, using an Omron HEM-705CP fully automatic digital blood-pressure monitor (Omron Healthcare Europe B.V., Hoofddorp, The Netherlands), which was validated by the British Hypertension Society.

**Experimental techniques**

**DNA analysis.** Restriction fragment length polymorphisms in the VDR gene were determined by PCR followed by digestion of the amplified PCR product with the Fok I restriction endonuclease as described by Gross et al. (1996). Following restriction endonuclease digestion, VDR genotypes were determined by ethidium bromide–u.v.-B illumination of the fragments separated on agarose (20 g/l) gel. Homozygous absence of the Fok I restriction fragment length polymorphism site (designated FF) resulted in two fragments of 265 bp and sixty-nine bp, while homozygous presence of the site (ff) resulted in two fragments of 196 and sixty-nine bp. Heterozygotes (Ff) exhibited all three fragments. Subjects carrying one or more f (Fok I) alleles were designated f + (i.e. Ff and ff VDR genotypes), while those not carrying an f allele were designated f− (i.e. FF VDR genotype). This VDR genotype stratification approach has recently been used by Tofteng et al. (2002), who showed that the presence of an f VDR allele was associated with lower bone mineral density in Danish postmenopausal women compared with those without the f allele.

**Urinary type I collagen cross-linked N-telopeptides.** NTx was measured in the urine samples by an ELISA (Osteomark®, Ostex International, Inc., WA, USA). The intra-assay CV was 5 %. Inter-assay variation was avoided by analysing all samples from an individual in the same run.

**Urinary creatinine.** Creatinine was determined in urine samples using a diagnostic kit (Metra Creatinine Assay Kit, catalogue no. 8009; Quidel Corporation, San Diego, CA, USA). The intra-assay CV was 1-6 %. Inter-assay variation was avoided by analysing all samples from an individual in the same run.

**Urinary calcium, sodium and potassium.** Ca was analysed in duplicate in urine samples by atomic absorption spectrophotometry (Spectr AA-600; Varian Australia Ltd, St Helens Victoria, Australia) after appropriate dilution with LaCl₃ solution (5 g/l; BDH Ltd, Poole, Dorset, UK). A range of Ca standards was used to obtain a Ca calibration curve. The intra- and inter-assay CV for Ca were 2·8 and 7·8 % respectively. Na and K were determined in the urine samples by flame photometry (Jenway PFP7; ACB Ltd, Dublin, Republic of Ireland) using appropriate Na and K standards. The intra- and inter-assay CV for Na were 3·8 and 6·9 %, and for K were 4·5 and 9·3 % respectively.

**Urinary nitrogen level.** N was measured in urine samples using a modification of the Kjeldahl method (Association of Official Analytical Chemists, 1995). The intra-assay CV was 7·6 % and inter-assay variation was avoided by analysing all samples from an individual in the same run.

**Serum osteocalcin and bone-specific alkaline phosphatase.** Bone-specific alkaline phosphatase levels were measured in serum samples using a recently developed ELISA (Alkphase-B™; MetraBiosystems Inc., Mountain View, CA, USA). The intra-assay CV was 4·5 %. Osteocalcin levels were measured in serum samples using an ELISA (N-MID™; Osteometer Biotech, Osteopark, Denmark). The intra-assay CV was 11 %. Inter-assay variation for both serum osteocalcin and bone-specific alkaline phosphatase was avoided by analysing all samples from an individual in the same run.

**Plasma parathyroid hormone.** Samples were analysed in duplicate for intact parathyroid hormone (PTH) with a chemiluminescent immunoassay (IMMULITE™; Diagnostic Products Corporation, Los Angeles, CA, USA). The intra-assay CV for this assay was 5·8 %. Inter-assay variation was avoided by analysing all samples from an individual in the same run.

**Serum 25-hydroxycholecalciferol.** Serum proteins were precipitated with ethanol, and deproteinized serum was subsequently applied to a monofunctional saline (MF) C₁₈ solid-phase extraction column (Isolute®; International Sorbent Technology, Glamorgan, Wales, UK) for elution of the 25-hydroxycholecalciferol (25(OH)D₃) fraction with ethylacetate–n-heptane. The extracted 25(OH)D₃ was injected onto an HPLC-system (Waters, Milford, MA, USA) equipped...
with a 600 controller and pump, a refrigerated 717 Plus Autosampler, a 996 Diode Array Detector (set at 220–320 nm) for detection, and a 2487 Absorbance Detector (set at 265 nm) for quantification. The HPLC column used for separation was a cyanopropyl (Luna; Phenomenex, Torrance, CA, USA) in which 25(OH)D3 and 1,25-dihydroxycholecalciferol (1,25(OH)2D3) were eluted separately with 2-propanol–heptane. However, none of the samples contained 25(OH)D3; the intra-assay CV for 25(OH)D3 was 6.0%.

The accuracy of the analysis was monitored by participation in the vitamin D external quality assessment scheme (DEQAS; Charing Cross Hospital, London, UK).

Serum 1,25-dihydroxycholecalciferol. A radioimmunoassay (65100E; DiaSorin, Stillwater, MN, USA) was used for the quantification of 1,25(OH)2D3 levels. The manufacturer’s method was modified slightly as solid-phase extraction was performed on MF C18 columns (Isolute; International Sorbent Technology). The intra-assay CV for this assay was 12.6%. The accuracy of the analysis was monitored by participation in the vitamin D external quality assessment scheme (DEQAS; Charing Cross Hospital, London, UK).

Statistical analysis

Values are presented as means and standard deviations. Data for all variables were normally distributed (except for bone-specific alkaline phosphatase in the f–VDR group) as determined by the method of Kolmogorov & Smirnov and allowed for parametric tests of significance. Differences in age, height, weight, BMI and years since menopause between the two VDR genotype groups were examined by unpaired Student’s t tests. Nutrient intakes between each dietary period and between both genotype groups were compared using paired and unpaired Student’s t tests respectively. Differences between the two dietary regimens in biochemical indices of bone turnover and urinary excretion were examined by two-sample t tests. Nutrient intakes between the two VDR genotype groups were examined by two-sample t tests and ANOVA were used to test hypotheses about direct treatments effects (i.e. calciuric diet), carry-over effects and interactions.

Results

Baseline blood pressures in all twenty-six postmenopausal women were within the World Health Organization (1999) targets (i.e. <140 and <90 mmHg for systolic and diastolic blood pressure respectively). Daily urinary Na output by these women while on their habitual diet ranged between 37 and 178 mmol/d.

All twenty-six women completed the dietary intervention study. However, two subjects had no increase in daily urinary Na or N output on the high-Na, high-protein diet and, therefore, were considered to be protocol violators and were excluded from the analysis.

Dietary intakes of energy, Ca, Mg, P, K or fibre (NSP) were similar during the two dietary regimens (Table 2). Dietary intakes of caffeine were similar during the two dietary regimens (306 (SD 126) mg on the basal diet v. 301 (SD 157) mg on the calciuric diet; P = 0.840). There was no significant difference in body weight between the two dietary regimens (63.5 (SD 10.6) kg on the basal diet v. 63.6 (SD 10.4) kg on the calciuric diet; P = 0.542).

The effects of increasing Na and protein intake from the basal diet to the calciuric diet for 28 d on urinary and serum biochemical variables, and on blood pressure are shown in Table 3. There were no significant differences in systolic or diastolic blood pressure of the women between the two diets. Compared with the basal diet, significant increases were observed on the calciuric diet for mean urinary Na, Ca, K and N.

There were no significant differences between the two diets for mean urinary creatinine or mean serum concentrations of 25(OH)D3 or 1,25(OH)2D3 or mean plasma PTH (Table 3). Urinary excretion of NTx/creatinine was significantly (P < 0.05) higher when subjects were fed the calciuric diet compared with the basal diet (Table 3). There were no significant differences between the two diets for mean levels of serum biochemical markers of bone formation (serum bone-specific alkaline phosphatase or osteocalcin) (Table 3).

There were no significant differences between the f– and f+ VDR genotype groups for age, weight, height or BMI (Table 4) or for baseline biochemical indices or

\[\text{Table 2. Intakes of selected nutrients from the final 4 d during low-sodium, usual-protein and high-sodium, high-protein dietary periods for apparently healthy postmenopausal women (n 24)*} \]

(Mean values and standard deviations)

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Low-Na, usual-protein</th>
<th>High-Na, high-protein</th>
<th>Statistical significance of effect: P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Energy (kJ/d)</td>
<td>8061</td>
<td>3094</td>
<td>8132</td>
</tr>
<tr>
<td>Fibre (NSP)  (g/d)†</td>
<td>17.8</td>
<td>5.0</td>
<td>18.2</td>
</tr>
<tr>
<td>Ca (mg/d)</td>
<td>733</td>
<td>221</td>
<td>689</td>
</tr>
<tr>
<td>P (mg/d)</td>
<td>3469</td>
<td>1640</td>
<td>3437</td>
</tr>
<tr>
<td>Mg (mg/d)</td>
<td>346</td>
<td>109</td>
<td>342</td>
</tr>
</tbody>
</table>

* For details of subjects and procedures, see Table 1 and p. 42.
† Total NSP measured according to Englyst & Cummings (1988).
blood pressure (results not shown). In addition, there were no significant differences in the dietary intakes of energy, Ca, P, K, Mg, caffeine or fibre between the calciuric and basal diets in either VDR genotype groups, or between the VDR genotype groups consuming either the calciuric or basal diets (results not shown).

There were no significant differences in serum osteocalcin, bone-specific alkaline phosphatase or vitamin D metabolites, or plasma PTH between the basal and calciuric diets in either VDR genotype groups (Table 5).

Compared with the basal diet, significant increases were observed on the calciuric diet for mean urinary Na, Ca, K and N in both VDR genotype groups (Table 5). Urinary excretion of NTx/creatinine was significantly higher in subjects carrying one or more fVDR alleles when consuming the calciuric diet compared with the basal diet (Table 5). On the other hand, there was no effect of the calciuric diet on urinary NTx/creatinine in subjects not carrying a fVDR allele (Table 5).

### Discussion

In the present study, the average increase in urinary Ca in response to increased dietary Na and protein in the twenty-four postmenopausal women who took part in the dietary intervention trial was 0.81 mmol/d. It is well established that increasing dietary Na intake within the usual range of dietary intakes increases urinary Ca excretion (Shortt & Flynn, 1990; Ginty et al. 1998b). This dependence of urinary Ca excretion on urinary Na excretion has been attributed to the existence of linked or common re-absorption pathways for both ions in the convoluted portion of the proximal tubule and thick ascending loop of Henle (Shortt & Flynn, 1990). There is also considerable evidence that increasing dietary protein intake within the usual range of dietary intakes increases urinary Ca excretion (for reviews, see Kerstetter & Allen, 1990, 1994; Heaney, 1993, 1998; Massey, 1998). Protein-induced calciuria has been attributed to an increased glomerular filtration rate.
Calciuric diet and postmenopausal bone metabolism

Table 5. Urinary and serum biochemical variables and blood pressure in apparently healthy postmenopausal women in both vitamin D receptor (VDR) genotype groups during low-sodium, usual-protein and high-sodium, high-protein dietary periods†‡

(Mean values and standard deviations)

<table>
<thead>
<tr>
<th>VDR genotype group</th>
<th>Diet period…</th>
<th>Low-Na, usual-protein</th>
<th>Mean</th>
<th>SD</th>
<th>Low-Na, high-protein</th>
<th>Mean</th>
<th>SD</th>
<th>Low-Na, usual-protein</th>
<th>Mean</th>
<th>SD</th>
<th>Low-Na, high-protein</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na (mmol/d)</td>
<td>f− (n 14)</td>
<td>60·2</td>
<td>26·3</td>
<td></td>
<td>132·2**</td>
<td>40·0</td>
<td></td>
<td>60·5</td>
<td>27·1</td>
<td></td>
<td>129·3**</td>
<td>36·0</td>
<td></td>
</tr>
<tr>
<td>K (mmol/d)</td>
<td></td>
<td>65·8</td>
<td>20·2</td>
<td></td>
<td>72·4**</td>
<td>14·8</td>
<td></td>
<td>69·0</td>
<td>15·4</td>
<td></td>
<td>73·8**</td>
<td>26·5</td>
<td></td>
</tr>
<tr>
<td>Ca (mmol/d)</td>
<td></td>
<td>3·54</td>
<td>1·26</td>
<td></td>
<td>4·63**</td>
<td>1·57</td>
<td></td>
<td>3·56</td>
<td>1·33</td>
<td></td>
<td>4·36**</td>
<td>1·24</td>
<td></td>
</tr>
<tr>
<td>N (mmol/d)</td>
<td></td>
<td>749</td>
<td>208</td>
<td></td>
<td>880**</td>
<td>166</td>
<td></td>
<td>718</td>
<td>165</td>
<td></td>
<td>830**</td>
<td>121</td>
<td></td>
</tr>
<tr>
<td>Creatinine (mmol/d)</td>
<td></td>
<td>8·6</td>
<td>1·4</td>
<td></td>
<td>8·3</td>
<td>1·5</td>
<td></td>
<td>9·1</td>
<td>1·8</td>
<td></td>
<td>9·0</td>
<td>1·7</td>
<td></td>
</tr>
<tr>
<td>NTX (nmol BCE/mmol creatinine)</td>
<td>34·3</td>
<td>9·0</td>
<td>39·9</td>
<td>12·3</td>
<td>34·4</td>
<td>12·6</td>
<td>43·2</td>
<td>12·5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serum 25(OH)D3 (nmol/l)</td>
<td>68·4</td>
<td>13·5</td>
<td>70·0</td>
<td>15·4</td>
<td>74·2</td>
<td>13·8</td>
<td>71·8</td>
<td>11·6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serum 1,25(OH)2D3 (nmol/l)</td>
<td>112</td>
<td>23</td>
<td>113</td>
<td>28</td>
<td>132</td>
<td>10</td>
<td>144</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serum B-alkphase (UI)</td>
<td>25·7</td>
<td>9·4</td>
<td>27·1</td>
<td>10·4</td>
<td>27·5</td>
<td>5·5</td>
<td>27·6</td>
<td>6·1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serum osteocalcin (μg/l)</td>
<td>26·6</td>
<td>7·1</td>
<td>25·8</td>
<td>8·9</td>
<td>26·6</td>
<td>11·8</td>
<td>26·9</td>
<td>10·2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma PTH (pmol/l)</td>
<td>2·9</td>
<td>1·2</td>
<td>3·0</td>
<td>1·3</td>
<td>3·3</td>
<td>1·6</td>
<td>3·2</td>
<td>1·0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NTX, type I collagen cross-linked N-telopeptides; BCE, bone collagen equivalents; 25(OH)D3, 25-hydroxycholecalciferol; 1,25(OH)2D3, 1,25-dihydroxycholecalciferol; B-alkphase, bone-specific alkaline phosphatase; PTH, parathyroid hormone.

Direct treatment effect (i.e. calciuric diet) was analysed for each biochemical index within a VDR genotype group by two sample t tests of within group differences after testing for carry-over effects: **P＜0·01. (No significant carry-over effects were found.)
† For details of subjects and procedures, see Table 1 and p. 42.
‡ For details of VDR genotype groups, see p. 44.

and a decreased tubular reabsorption of Ca, caused by increased excretion of sulfate derived from catabolism of S-containing amino acids native to the protein (Kim & Linkswiler, 1979; Schuette et al. 1980). There are no comparable results in the literature from trials with human subjects on the combined effect of increased Na and protein intake on urinary Ca excretion in adults. There is some evidence from animal studies that the calciuric effects of high Na and high protein intakes may be additive (Goulding & Swaminathan, 1994). To place the Na and/or protein-induced calciuria observed in the present study in the context of bone health, it has been estimated that a net deficit of only 1 mmol Ca/d would result in losing one-third of the Ca contained in the typical adult skeleton in just over 20 years, unless a compensatory increase in the efficiency of intestinal Ca absorption and/or decrease in endogenous loss of Ca occurred (Shortt & Flynn, 1990; Sellmeyer et al. 2002).

The increase in urinary Ca was not influenced by other dietary factors (e.g. Ca, Mg, P, K or fibre) that have been reported to influence urinary Ca excretion (Heaney & Recker, 1982; Massey & Wise, 1984), since the intakes of these were similar for the basal and calciuric diets.

In the present study, urinary excretion of K was significantly higher when subjects consumed the calciuric diet compared with the basal diet. While there are no comparable results in the literature from trials with human subjects on the combined effect of increased Na and protein intake on urinary K excretion, previous studies of postmenopausal women have reported a lack of effect of increasing dietary Na alone on K excretion (Zarkadas et al. 1989; Lietz et al. 1997; Sellmeyer et al. 2002). However, other studies have reported an increased urinary K excretion with increasing Na intake in adults. For example, Castenmiller et al. (1985) showed that increasing Na intake in adult men significantly increased urinary K as well as urinary Ca. Bell et al. (1992) reported that increasing the Na content of a control diet fed to healthy young women increased urinary K, while Ginty et al. (1998a) found a significant positive correlation between urinary Na and K in a group of healthy young adults.

In the present study, increasing the dietary Na and protein significantly increased the urinary excretion of N (P＜0·001). This is in agreement with the findings of several studies in which urinary N increased significantly in adults when dietary protein was increased (Draper et al. 1991; Kerstetter et al., 1998).

Urinary NTX excretion was about 19% higher in postmenopausal women in the present study when consuming the calciuric diet compared with the basal diet. NTX is considered a sensitive and specific marker of bone resorption (Rosen et al. 1994). While there are no comparable results from trials with human subjects in the literature on the combined effect of increased Na and protein intake on bone resorption, the effect of increased Na intake on bone resorption was investigated in postmenopausal women (Evans et al. 1997; Lietz et al. 1997; Sellmeyer et al. 2002). In one crossover trial, fourteen postmenopausal women were randomized to a fixed diet containing 20 mmol (800 mg) Ca/d and either 60 or 170 mmol Na/d for 8 d and then crossed-over to the alternative diet for a further 8 d (Lietz et al. 1997). Urinary Dpyr excretion was unaffected by Na intake. In a second crossover trial, eleven postmenopausal women (with a mean usual Ca intake of 18 mmol (741 mg)/d) were randomized to a low (50 mmol/d) or high (300 mmol/d) Na diet for 7 d and then crossed-over to the alternative diet for a further 7 d (Evans et al. 1997). There was a significant increase (27%, P=0·024) in urinary Dpyr excretion on the high-Na diet. Finally, Sellmeyer et al. (2002) recently reported
that when postmenopausal women, who received a daily supplement of 12 mmol (500 mg) Ca in addition to their usual diet and who were adapted to a low-Na diet (87 mmol/d) for 3 weeks, were switched to a high-Na (225 mmol/d) diet for a further 4 weeks, urinary NTx levels were significantly increased (by 23%, P<0.001).

There are a few studies that have investigated the influence of increased protein intake on the rate of bone resorption, but none that have investigated this association in postmenopausal women. Schuette et al. (1981) reported that urinary hydroxyproline was significantly increased (by 32%, P<0.05) in sixteen young men when the protein content of the diet (with a fixed dietary Ca level) of 20 mmol (800 mg)/d from 45 to 129 g/d for 4 d led to an increased urinary excretion of NTx (by 47%, P<0.05) in healthy young women. However, increasing the protein content of the diet from 63 to 129 g/d for 4 d had no effect on urinary NTx levels in that study. Shapses et al. (1995) found that urinary hydroxyproline, pyridinoline and Dpyr were unaffected in seven young men and eight young women by increasing dietary protein content from 0.44 to 2.71 g/kg body weight per d for 5 d. However, in that study, dietary Ca was increased from 11 (423 mg) to 40 mmol (1589 mg)/d concomitant with the increase in dietary protein, potentially obscuring an effect of dietary protein on bone resorption (Kerstetter et al. 1999).

The calciuric diet in the present study had no effect on serum osteocalcin or bone-specific alkaline phosphatase levels. McParland et al. (1989) reported that in addition to an increased rate of bone resorption (as shown by increased urinary hydroxyproline excretion), serum osteocalcin levels were also increased in postmenopausal women supplemented with 100 mmol Na/d for 10 d. However, another Na intervention study reported a lack of effect in the present study as well as in that of Evans et al. (1997). The lack of effect in the present study as well as in that of Evans et al. (1997), however, could possibly be due to their relative short duration; bone formation, although coupled to resorption, is separated by approximately 6 weeks (Eriksen et al. 1984).

The increased rate of bone resorption observed in postmenopausal women in the present study may be as a consequence of a lack of, or an incomplete, intestinal adaptation to the Na and/or protein-induced calciauria. Breslau et al. (1985) found no increase in intestinal Ca absorption in seven osteoporotic postmenopausal women when Na intake was increased from 10 to 250 mmol/d while dietary Ca was maintained at 10 mmol/d. Two other studies have reported a lack of effect of increasing dietary Na on Ca absorption, using Sr absorption as an index in postmenopausal women (McParland et al. 1989; Evans et al. 1997); however, the precision of this method may have been too low to detect a change. Similarly, increasing the protein intake in postmenopausal women (Draper et al. 1991) or elderly adults (Dawson-Hughes & Harris, 2002) appears to have no effect on the efficiency of intestinal Ca absorption. In the present study, there was no effect of the calciuric diet on serum 1,25(OH)2D3 levels, an important mediator of the adaptive component of Ca absorption. This is in agreement with the findings of some studies that found no effect of increasing dietary protein (Schuette et al. 1980; Na (Breslau et al. 1982; McParland et al. 1989) on circulating 1,25(OH)2D3 levels in postmenopausal women and older adults. There is evidence that serum PTH is increased in association with Na-induced calciauria (McCarron et al. 1981; Breslau et al. 1982). There was no significant effect of the calciuric diet on plasma PTH levels in postmenopausal women in the present study. This is in agreement with the findings of some Na-loading studies (Evans et al. 1997; Lietz et al. 1997; Sellmeyer et al. 2002) and some studies of increased protein intake (Schuette et al. 1980, 1981; Draper et al. 1991) in postmenopausal women. However, interpretation of studies that examine PTH changes are made difficult by differences in sensitivity of the radioimmunoassays used, the pulsatile nature of serum PTH concentrations, the half-life of intact PTH (4 min) and the possible haemodilution effect of Na loading (Jubiz et al. 1972; Slatopolsky et al. 1982; Garel et al. 1987; Chan et al. 1992, for review, see Massey & Whiting, 1996).

In the present study, postmenopausal women carrying an f VDR allele had significantly elevated levels of urinary NTx (by about 25-6%) when consuming the calciuric diet compared with that during the basal dietary period, whereas those without the f allele had no increase in urinary NTx when placed on the calciuric diet. Interestingly, the increment in urinary Ca with additional Na and protein was of a similar magnitude in the two VDR genotype groups. Furthermore, there were no differences in the responses of the other serum or urinary variables to the calciuric diet between the genotype groups. There were also no differences in dietary factors (e.g. Ca, Mg, P, K, caffeine or fibre), which have been reported to influence Ca and bone metabolism between the genotype groups. It would appear from these findings that the subjects carrying one or more f VDR alleles were less able to adapt to the calciauria than those without the f allele. It is possible that in subjects without the f allele(s) the Na- and protein-induced urinary Ca loss is compensated for by increased Ca absorption and/or reduced endogenous Ca loss rather than increased bone resorption, whereas the reverse may be true in those carrying the f allele. Ames et al. (1999) showed that children (White and Mexican-American, aged 7.5–12.0 years) with the FF (i.e. f−) VDR genotype had 52.9% (P<0.02) and 29.6% (P=0.08) greater Ca absorption as compared with children with the ff and Ff (i.e. f+) VDR genotypes respectively. Therefore, the f VDR allele may modulate the adaptive capacity of intestinal Ca absorption in response to dietary calcicuric factors. The mechanism by which this occurs is not clear and warrants further investigation. VDR molecules encoded by the f allele initiate translation from an upstream ATG (at the site of the Fok I polymorphism) and are three amino acids longer than the F allele products, and moreover,
the protein encoded by the f allele produced 1.7-fold lesser transactivation of transcription from a promoter containing a vitamin D-responsive element than did the F allele product (Arai et al. 1997).

The influence of another dietary calciuric factor, i.e. high caffeine intake (>300 mg/d), on skeletal integrity has recently been shown to interact with the VDR genotype. Rapuri et al. (2001) reported that postmenopausal women with the tt genetic variant of VDR appeared to be at a greater risk for the deleterious effect a high caffeine intake on vertebral bone loss over 3 years compared with women with the TT VDR genotype.

Finally, there was no effect of a high Na (and high protein) diet over 4 weeks on body weight in the present study. While weight gains resulting from an increase in plasma volume in response to abrupt increases in dietary NaCl (an additional 235–240 mmol Na/d) were reported in some short-term (7 d) studies (Kurtz et al. 1987; Morris et al. 1999), Zarkadas et al. (1989) found no effect of increasing salt intake (an additional 51 and 102 mmol Na/d) on body weight in postmenopausal women over 5 d. The apparent lack of effect in the present study could be due to the relatively low level of NaCl supplementation administered (an additional 115 mmol Na/d) or because the subjects had achieved Na balance by the end of the 4 weeks (it usually takes 3–5 d for complete restoration of NaCl balance after altering NaCl intake), as suggested by Zarkadas et al. (1989).

In conclusion, the effect of the calciuric diet on biochemical markers of bone resorption in postmenopausal women in the present study suggests that the Na- and protein-induced urinary Ca loss is compensated for by increased bone resorption rather than by a complete adaptation at the level of intestinal Ca absorption and/or endogenous Ca loss in women who carry one or more of the f VDR alleles. This group represents over half of all VDR alleles. This group represents over half of all postmenopausal women. Until such time as an individual’s genotype are known, it may be prudent to make dietary recommendations based on the assumption that each person may have a genetic susceptibility to osteoporosis. Therefore, it would also seem prudent to recommend moderate protein and Na intake for postmenopausal women.

Acknowledgement

This work was carried out with financial support from the European Commission Quality of Life Fifth Framework Programme. QLK1-CT 1999-000752.

References


