Fish-bone peptide increases calcium solubility and bioavailability in ovariectomised rats

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Fish-bone peptides (FBP) with a high affinity to Ca were isolated using hydroxyapatite affinity chromatography, and FBP II with a high ratio of phosphopeptide was fractionated in the range of molecular weight 5·0–1·0 kDa by ultramembrane filtration. In vitro study elucidated that FBP II could inhibit the formation of insoluble Ca salts in neutral pH. In vivo effects of FBP II on Ca bioavailability were further examined in the ovariectomised rat. During the experimental period, Ca retention was increased and loss of bone mineral was decreased by FBP II supplementation in ovariectomised rats. After the low-Ca diet, the FBP II diet, including both normal level of Ca and vitamin D, significantly decreased Ca loss in faeces and increased Ca retention compared with the control diet. The levels of femoral total Ca, bone mineral density, and strength were also significantly increased by the FBP II diet to levels similar to those of the casein phosphopeptide diet group (no difference; P>0·05). In the present study, the results proved the beneficial effects of fish-meal in preventing Ca deficiency due to increased Ca bioavailability by FBP intake.

Fish-bone peptides: Calcium solubility: Ovariectomised rats: Calcium bioavailability

The major source of Ca is the diet, and the most common and trusted source of Ca is milk or other dairy products (Anderson & Garner, 1996). Dairy products contain a high content of casein. Casein phosphopeptides (CPP) derived from the intestinal digestion of casein have been shown to enhance bone calcification in rats (Lee et al. 1980; Tsuchita et al. 1993). Such CPP have the capacity to chelate Ca and to prevent the precipitation of Ca phosphate salts (Berrocal et al. 1989), thereby increasing the amount of soluble Ca availability for absorption across the mucosa (Yuan & Kitts, 1991, 1994).

However, some oriental people do not drink milk due to lactose indigestion and intolerance, which make them allergic to milk. Thus, there have been many studies on various Ca supplements as alternatives (for examples, soya protein isolate, fructo-oligosaccharide, fish-meal, etc), which may affect Ca bioavailability (Brouns & Vermeer, 2000; Larsen et al. 2000, 2003; Kumagai et al. 2004). As reported by Larsen et al. (2000), the intake of small fish with bones could increase Ca bioavailability in rats, and small fish might be an important Ca dietary supplement, especially in population groups with low intakes of milk and dairy products.

Annually, more than 50 % of total fishery products (over 120 million tons) are discarded as inedible by-products, such as bone, skin, fins, internal organs and head. Thus, many studies have been performed to utilise the large amounts of protein, oil, minerals, carbohydrate and nucleic acid originating from fishery by-products, and to improve their functional properties (Nair & Gopakumar, 1982; Rodriguez-Estrada et al. 1994; Nagai & Suzuki, 2000; Kim et al. 2001, 2003; Shahidi & Janak Kamil, 2001). However, studies on the utilisation of organic components or minerals in fish bone are scarce (Kim et al. 1997; Larsen et al. 2000, 2003). In our previous study (Jung et al. 2005), fish-bone phosphopeptide with the high affinity to Ca had been isolated from hoki (Johnius belengerii) skeletons discarded from industrial processing. The present study in vivo was undertaken to evaluate the beneficial effects of fish-bone peptide (FBP) as a Ca fortifier.

Materials and methods

Preparation of fish-bone peptides with calcium-binding activity

FBP with a high affinity to Ca were isolated from hoki bone-protein hydrolysates using a hydroxyapatite affinity column. Hoki bone powder was digested with Thunnus thynnus (blue-fin tuna) intestine crude enzyme (pH 9·0; 40°C; enzyme–substrate, 1:100; substrate concentration, 1 %) for 48 h according to the method of Kim et al. (2003). After incubation at 100°C for 5 min to inactivate the enzyme, the tuna intestine crude enzyme-digested fish-bone hydrolysates were filtered and demineralised on a Chelex 100 resin (Bio-Rad, Richmond, CA, USA) column. Then the Ca-binding fraction was eluted throughout a hydroxyapatite affinity column (20 × 80 mm, 21 Aug 2017 at 11:51:17, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1079/BJN20051615
Macroprep ceramic hydroxyapatite type 1; Bio-Rad) according to a previous method (Jung et al. 2005). After affinity chromatography, the peptide fraction with the highest Ca affinity was collected and fractionated into three kinds of peptides with different molecular weights (MW > 5 kDa, 5–1 kDa and < 1 kDa) using an ultramembrane filter system with MW 5.0 and 1.0 kDa cut-off membranes (SM165; Sartorous, Göttingen, Germany). After chemical analysis, the fractions were lyophilised.

Chemical analysis

Protein concentration in sample solutions was determined by the method of Lowry et al. (1951) using bovine serum albumin as a standard. After demineralisation of samples with Chelex-100 (Bio-Rad), P was determined by the colorimetric method, using a phospoprotein phosphate assay kit (Pierce Biotechnology, Inc., Rockford, IL, USA), and phosvitin (Sigma Chemical Co., St Louis, MO, USA) was used as a standard. Amino acid composition was analysed according to our previous study (Jung et al. 2005). Ca concentration in sample solutions was measured by a flame atomic absorption spectrometer (Simatzu AA-680; Simatzu Co., Tokyo, Japan) fitted with a hollow cathode lamp. Instrumental conditions were wavelength ¼ 422·8 nm, slit ¼ 0·7 nm, acetylene flow ¼ 14·0 l/min, nebuliser ¼ spoiler. Lanthanum solution was added to 0·1 % (w/v) sample solutions.

In vitro calcium-binding assay

Ca-binding assays were performed according to the method of Jung et al. (2005). Various concentrations of FBP up to 500 mg/l were mixed with 5 mM-CaCl2 and 20 mM-sodium solutions.

Experimental animals and diets

Sprague–Dawley ovariectomised rats (n 24; 3 months old) were obtained from Korea Research Institute of Daejeon (Daejeon, Korea). The rats were housed in individual shoe-box cages in a temperature- and humidity-controlled room (22 ± 2 °C and 60 ± 5 % relative humidity) with a 12 h light–dark cycle in accordance with the Guidelines on the Use of Living Animals in Scientific Investigations (Biological Council, 1987). As shown in Table 1, all experimental diets were prepared according to the AIN-76 diet (Anonymous, 1977) with slight modification. The low-Ca diet used in the present study was made from Ca-free AIN-76 salt mix (Ralston Purina International Co., St Louis, MO, USA) with added CaCO3 (0·175 g/kg) (Shinyo Pure Chemicals Co., Osaka, Japan) as the Ca source. After ovariectomy, rats were fed ad libitum with the low-Ca diet and deionised water for 6 weeks. The rats were then randomly assigned to the control and two experimental groups (eight rats per group). The control group was switched to a normal-Ca diet including CaCO3 (17·5 g/kg) for 6 weeks. Rats in the experimental groups were fed on the normal-Ca diet including CPP type II (50 g/kg) produced by Meiji Seika Co. Ltd (Tokyo, Japan) and FBP II (50 g/kg).

Sampling and analytical methods

Body weight was recorded once per week throughout the 6-week experimental diet. During the 4 d metabolic balance study at the end of treatment, the amount of food and Ca intake were monitored by housing each rat individually according to the method of Zafar et al. (2004). Urinary Ca and faecal Ca excreted were measured by a flame atomic absorption spectrometer. Ca retention (balance) was calculated as: Ca intake – faecal Ca – urinary Ca. After 6-week feeding periods, the rats were fasted overnight and killed under pentobarbitone anaesthesia. Blood collected from carotid bleeding was centrifuged to separate serum, and serum Ca was measured by an automatic analyser (ARKRAY model SP-4410; Kyoto Daiichi Kagaku Co., Ltd, Kyoto, Japan). Right femurs were excised and connective tissues were cleared. After measuring length and weight, the breaking force of femurs were excised and connective tissues were cleared. After measuring length and weight, the breaking force of femoral centre was analysed by an INSTRON universal testing instrument (model 1011; Instron Co., Canton, MA, USA). Data were expressed as peak breaking force of femur breaking (kg unit). Broken femurs were dissolved in 3 ml 70 % HNO3 individually. The diluted femur solution was analysed for total Ca by flame atomic absorption spectrometry. Bone

In vivo effects of fish-bone peptides

In vivo effects of fish-bone peptides

Table 1. Composition of the modified AIN-76 diet

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Low-Ca diet</th>
<th>Control</th>
<th>CPP</th>
<th>FBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casein</td>
<td>200·0</td>
<td>200·0</td>
<td>150·0</td>
<td>150·0</td>
</tr>
<tr>
<td>CPP</td>
<td>–</td>
<td>–</td>
<td>50·0</td>
<td>–</td>
</tr>
<tr>
<td>FBP</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>50·0</td>
</tr>
<tr>
<td>L-Methionine</td>
<td>3·0</td>
<td>3·0</td>
<td>3·0</td>
<td>3·0</td>
</tr>
<tr>
<td>Maize starch</td>
<td>150·0</td>
<td>150·0</td>
<td>150·0</td>
<td>150·0</td>
</tr>
<tr>
<td>Sucrose</td>
<td>499·8</td>
<td>482·5</td>
<td>482·5</td>
<td>482·5</td>
</tr>
<tr>
<td>Cellulose</td>
<td>50·0</td>
<td>50·0</td>
<td>50·0</td>
<td>50·0</td>
</tr>
<tr>
<td>Maize oil</td>
<td>50·0</td>
<td>50·0</td>
<td>50·0</td>
<td>50·0</td>
</tr>
<tr>
<td>Mineral mix*</td>
<td>35·0</td>
<td>35·0</td>
<td>35·0</td>
<td>35·0</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0·175</td>
<td>17·5</td>
<td>17·5</td>
<td>17·5</td>
</tr>
<tr>
<td>Vitamin mix†</td>
<td>10·0</td>
<td>10·0</td>
<td>10·0</td>
<td>10·0</td>
</tr>
<tr>
<td>Choline bitartrate</td>
<td>2·0</td>
<td>2·0</td>
<td>2·0</td>
<td>2·0</td>
</tr>
</tbody>
</table>

CPP, casein phosphopeptide; FBP, fish-bone phosphopeptide.

*Ca-free AIN-76 mineral mix contains (g/kg): potassium phosphate monobasic, 500·00; sodium chloride, 74·00; magnesium sulfate, 36·20; magnesium oxide, 11·90; manganese carbonate, 3·50; ferric citrate, 6·60; zinc carbonate, 1·60; copper carbonate, 0·30; potassium iodate, 0·01; sodium selenite, 0·01; chromium potassium sulphate, 0·55; finely powdered sucrose, 365·93.

†AIN-76A vitamin mixture contains (g/kg): thiamin HCl, 0·60; riboflavin, 0·60; pyridoxine HCl, 0·70; niacin, 3·0; calcium pantothenate, 1·60; folic acid, 0·20; biotin, 0·02; vitamin B2, 1·0; vitamin A palmitate 0·80; vitamin D3 0·25; vitamin E acetate 10·00; menadione sodium bisulfite, 0·08; finely powdered sucrose, 981·15. For details of diets and procedures, see p. 124.

In vivo test of calcium absorption and bone mineral density in ovariectomised rats

The composition of the modified AIN-76 diet was based on the AIN-76 diet of the National Academy of Sciences (1970) as described. The following modifications were made. The vitamin mix contained (g/kg): thiamine HCl, 0·60; riboflavin, 0·60; pyridoxine HCl, 0·70; niacin, 3·0; calcium pantothenate, 1·60; folic acid, 0·20; biotin, 0·02; vitamin B2, 1·0; vitamin A palmitate 0·80; vitamin D3 0·25; vitamin E acetate 10·00; menadione sodium bisulfite, 0·08; finely powdered sucrose, 981·15. For details of diets and procedures, see p. 124.
mineral density of the distal region, defined as 5% of the whole length of the left femur, was determined by dual-energy X-ray absorptiometry (HITACHI BMD-IX; Hitachi Co., Tokyo, Japan).

**Statistical analysis**

ANOVA was performed with Duncan’s multiple range test using SAS to compare means (SAS Institute, Inc., Cary, NC, USA). The level of significance was \( P<0.05 \) for all statistical tests.

**Results**

**Chemical analysis and in vitro assay for calcium-binding activity**

FBP with Ca-binding activity were isolated using hydroxyapatite affinity chromatography according to our previous method (Jung et al. 2005). Chemical compositions of FBP I, II and III were analysed as shown in Table 2. The FBP II fraction with the distribution of MW 5.0–1.0 kDa mainly consists of 15.1% P (w/w) and 83.7% protein (w/w). It consisted of 27.95% glycine, 12.6% threonine, 9.7% alanine, 8.6% serine, 8.1% glutamate or glutamine, and 7.3% hydroxyproline (data not shown). In the assay for Ca-binding activity (Fig. 1), FBP II showed the highest affinity to Ca as compared with other fractions, but lower than that of CPP. The solubility of Ca was dependent on the concentration of FBP II, and 26.35 mg Ca/l was obtained at a concentration of 200 mg/l at pH 7.8. In the treatment of 200 mg CPP/l, 29.64 mg Ca/l was analysed in the supernatant fraction after the formation of insoluble salts.

**Body weight, food intake, calcium intake, calcium loss and retention**

No significant difference in body-weight gain, food intake, and total Ca intake was found among the three groups (Table 3). Serum Ca level was slightly elevated in both the CPP and FBP II diet groups \( (P<0.05) \), and higher values of Ca retention were shown in both dietary groups.

**Table 2. Chemical analysis of fish-bone phosphopeptides (FBP)***

<table>
<thead>
<tr>
<th>FBP</th>
<th>P (% w/w)</th>
<th>Protein (% w/w)</th>
<th>Distribution of MW (kDa)</th>
<th>Yield (% w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total*</td>
<td>6-5</td>
<td>92-7</td>
<td>&gt;29.0</td>
<td>100-0</td>
</tr>
<tr>
<td>FBP I</td>
<td>5-3</td>
<td>93-9</td>
<td>&gt;5.0</td>
<td>59-0</td>
</tr>
<tr>
<td>FBP II</td>
<td>15-1</td>
<td>83-7</td>
<td>5.0–1.0</td>
<td>17-6</td>
</tr>
<tr>
<td>FBP III</td>
<td>2-9</td>
<td>95-6</td>
<td>&lt;1.0</td>
<td>23-4</td>
</tr>
</tbody>
</table>

MW, molecular weight.

*Total FBP before fractionation. FBP I, II, and III with different MW were fractionated by ultramembrane filtration with 5.0 kDa and 1 kDa cut-off membranes.

**Femur analysis**

The effects of the FBP II diet on the femur are presented in Table 4. A significant increase of the femoral weight was observed in the FBP II compared with the control \( (P<0.05) \). An increase in the femoral total Ca was also found in the FBP II-fed animals. The treatment with FBP II increased the bone mineral density of the distal region \( (P<0.005) \) and the breaking force of the proximal region \( (P<0.005) \) in the femur.

**Discussion**

FBP with high Ca-binding activity were isolated using hydroxyapatite affinity chromatography according to our previous method (Jung et al. 2005), and the Ca-binding peptide FBP II with a high content of P (15.1%) was fractionated in the range of MW 5.0–1.0 kDa. It was composed of high contents of 27.95% glycine, 12.6% threonine, 9.7% alanine, 8.6% serine, 8.1% glutamate or glutamine, and 7.3% hydroxyproline. All essential amino acids except for tryptophan (below 0.1 mg tryptophan/100 mg total amino acids) were detected from egg yolk phosvitin/l, with 35% phosphate retention, and the solubility was higher than that of commercial CPP II. As reported by Hoang et al. (2003), Ca-binding phosphoproteins, such as osteocalcin, can recognise Ca on the surface of hydroxyapatite. Dohi et al. (1987) isolated two Ca-binding proteins with the \( \gamma \)-carboxyglutamic acid (gla protein) domain from bullfrog *Rana catesbiana* using hydroxyapatite affinity chromatography. The present study in vitro elucidated that FBP with the high affinity to Ca was produced from enzymic
hydrolysates using the hydroxyapatite affinity column and the MW cut-off ultramembrane filtration, and could increase Ca solubility in the presence of phosphate under the neutral pH. 

In vivo effects of FBP II on Ca bioavailability were further studied in the ovariectomised rats. Menopause is a time when oestrogen deficiency leads to accelerated bone resorption and negative bone balance. The present study was undertaken to evaluate the beneficial effects of FBP as a Ca fortifier in osteoporosis induced by ovariectomy and a concurrent low-Ca diet. During the experimental period corresponding to the menopause, the loss of bone mineral (Ca) was decreased by FBP II supplementation in the ovariectomised rats. After the low-Ca diet, the FBP II diet, including both normal levels of Ca and vitamin D, significantly decreased Ca loss in faeces and increased Ca retention as compared with the control. The levels of femoral total Ca, bone mineral density, and breaking strength were also significantly increased by the FBP II diet to a level similar to those of the CPP diet group (no difference; P>0.05). It illustrates that the increased Ca retention by FBP II intake led to the prevention of mineral loss in the osteoporosis-modelling rats.

As reported by Larsen et al. (2000), the intake of small fish with bones can increase Ca bioavailability, and the small fish may be an important source of Ca, especially in population groups with low intakes of milk and dairy products. In the present study, the results proved the beneficial effects of fishmeal in preventing Ca deficiency due to increased Ca bioavailability by FBP intake. Furthermore, it is possible to provide a novel nutraceutical with a high bioavailability for Ca to oriental people with lactose indigestion and intolerance and Ca-fortified supplements, such as fruit juice or Ca-rich foods, as alternatives to dairy products.

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References


