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Symposium on ‘Diet and bone health’

Phyto-oestrogens and bone health

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As oestrogen deficiency is the main cause in the pathogenesis of osteoporosis hormone-replacement therapy remains the mainstay for prevention. However, prophylaxis by hormone-replacement therapy is limited. Phyto-oestrogens, which are weakly-oestrogenic compounds present in plants, deserve particular mention because emerging data support the suggestion that they may prevent bone loss associated with the menopause. In the past few years extensive research using animal models has provided convincing data to indicate a significant improvement in bone mass or other end points following feeding with soyabean. Moreover, observational studies relate the lower incidence of osteoporosis among women in the Eastern world to a diet rich in phyto-oestrogens. However, it is not valid to extrapolate to the Western situation. The varied clinical trials that have been published suggest that isoflavones reduce bone loss in women in the early period post menopause, but a definitive result requires more investigations of the effect of phyto-oestrogens on bone health that have substantial sample size and are of long duration. In addition, the clinical efficacy of soya foods in preventing osteopenia depends on their intestinal metabolism. Thus, phyto-oestrogens are a source for putative innovative dietary health intervention for post-menopausal women. However, more data are necessary, particularly in relation to their effect on the risk of fracture.

Phyto-oestrogens: Osteoporosis: Post-menopausal women

Osteoporosis, a systemic skeletal disease characterized by a low bone mass and microarchitectural deterioration, is one of society’s most debilitating and costly diseases, particularly in elderly women and increasingly in men. It has become a worldwide problem that is expected to worsen in many countries with ageing populations; the lifetime risk for osteoporotic fracture is 40% for women and approximately 15% for men(1). This condition is characterized by an imbalance between the deposition of matrix and mineralization and the resorption activity resulting from an impairment in the remodelling process as a result of changes in the functional lifespan of osteoclasts and osteoblasts(2).

Hormonal changes during the menopausal transition, which ultimately result in a decline in oestrogen, play a pivotal role in the development of this chronic disease(3). Indeed, oestrogens exhibit a broad range of physiological activities that are important in the homeostatic regulation of many cells, including bone cells. In women the menopause initiates an accelerated phase of predominantly cancellous bone loss that declines rapidly over 5–10 years to become asymptotic, with a subsequent slow phase that continues indefinitely. Oestrogen deficiency affects remodelling in several ways: it increases the activation frequency of bone modelling units, which leads to higher bone turnover; it induces a remodelling imbalance by prolonging the resorption phase and shortening the formation phase. As a consequence, the volume of the resorption cavity increases beyond the capacity of the osteoblasts to refill it(4). Thus, hormone-replacement therapies have been the first line of treatment for osteoporosis(5). However, available evidence appears to suggest that the long-term use of hormone-replacement therapy has numerous side effects (e.g. risk for developing breast and uterine cancers and CVD)(6–8) that have led to a drastic reduction in the percentage of post-menopausal women on hormone-replacement therapy in the Western world.

Abbreviation: ER, oestrogen receptor.
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Currently, natural alternatives with oestrogen-like activities are being investigated as possible new strategies for the treatment of osteoporosis. As it is evident that the effects of oestrogen on bone to a large extent are mediated via activation of its oestrogen receptors (ER; oestrogen signalling in mammalian cells is primarily mediated at the molecular level by two members of the nuclear receptor superfamily, ERα and ERβ)\(^9\), there is a great need for new activators of ER that selectively reproduce only the beneficial effects of oestrogen. Moreover, in addition to existing drug therapies, certain lifestyle and nutritional factors are known to reduce the risk of osteoporosis. Indeed, research into human nutrition has led to an awareness of the health benefits that diet can offer by providing several naturally-occurring bioactive molecules such as the phytochemicals, which include the phyto-oestrogens (whose common biological roles are to protect plants from stress or to act as part of a plant’s defence mechanism) that can act as oestrogen mimics. While these natural secondary metabolites are widely occurring, being ubiquitous in higher plants, the major classes of current interest from a nutritional perspective are the isoflavones and the lignans, which are mainly found in soyabean and flaxseed respectively\(^10\) (although the lignans are much more widespread in plant foods, their investigation has been limited because of the complexity of measurement techniques). These compounds are capable of interacting with ER, showing both agonist and antagonist properties. A conspicuous feature of their non-steroidal chemical structure is the phenolic ring that is theoretically a pre-requisite for an oestrogenic activity (binding to the ER). They also share a pair of hydroxyl groups, one being a substituent of an aromatic A ring, while the second lies at the opposite end\(^11,12\). These phyto-oestrogens thus have potential as a putative and innovative dietary health intervention for post-menopausal women, and are currently being studied for the prevention of sex hormone-related diseases such as breast cancer and prostate cancer\(^13\), as well as post-menopausal osteoporosis\(^14–16\).

The rationale for phyto-oestrogens

Foods based on soyabean have generated much interest recently as a result of evidence that populations consuming large amounts of soyabeans have a lower risk of some chronic diseases, notably osteoporosis. Indeed, the marked differences in the incidence of clinically-diagnosed osteoporotic fractures within Europe and even worldwide (the lowest rate occurring in countries in the East and to the South) could be related to specific nutritional practices. However, identifying the individual or multiple components of the diet involved in the pathogenesis of osteoporosis is extremely difficult because of the complex interplay between lifestyle factors, genetics and many confounding variables. Soyabean, a legume that has been grown for thousands of years, is traditionally used to prepare both fermented and non-fermented foods and is a staple among Asian populations. Soya foods contain an array of biologically-active phytochemicals that may confer important health benefits. These compounds include the isoflavones, which have received considerable attention because of their oestrogen-like properties in certain tissues, including bone. Thus, some investigators have referred to them as naturally-occurring selective ER modulators\(^17,18\).

The biological effects of phyto-oestrogens have been characterized using DNA microarrays\(^19\). Gene expression profiling has demonstrated that 17β-oestradiol, genistein (one of the two major isoflavones) and the synthetic oestrogen diethylstilbestrol alter the expression of the same 179 genes in the intact immature mouse uterus (under conditions in which each compound produces an equivalent gravimetric and histological uterotrophic effect), including lactotransferrin, complement component 3 and c-fos\(^20\).

Phyto-oestrogens may therefore have potential for maintaining or modestly improving the bone mass of human subjects. A substantial amount of research carried out in recent years using animal models has provided convincing data to indicate that feeding soyabean results in higher circulating levels of bone markers and lower incidence of oestrogen-deficiency-related diseases such as breast cancer and prostate cancer\(^13\), as well as a lower incidence across human populations and individuals. Furthermore, Asian diets, which are particularly high in soyabean consumption and bone mineral density (see Table 1). However, it has been shown that extrapolation to the Western situation is not valid; a single component of a total lifestyle of such communities, in which several other significant lifestyle factors are operative, cannot be expected to show a definitive correlation with disease. Moreover, consumption of soyabean is very low within the Western population and phyto-oestrogen exposure varies substantially across human populations and individuals. Furthermore, Asian diets, which are particularly high in soyabean, result in isoflavone consumption as high as 1 mg/g body weight per d, with plasma isoflavone concentrations reaching 1 μM in Japanese subjects. In Europe circulating levels are usually <0.07 μM for omnivores, and 0.4-0.6 μM-isoflavones and 0.8-1.0 μM-lignans among vegetarians\(^22,23\). Another limitation is the window of exposure\(^24\).

Observational studies

Several studies have indicated a relationship between the lower incidence of oestrogen-deficiency-related diseases (i.e. osteoporosis) among women in Eastern countries and a diet rich in phyto-oestrogens. Moreover, a clear relationship has been demonstrated between the level of soyabean consumption and bone mineral density (see Table 1). However, it has been shown that extrapolation to the Western situation is not valid; a single component of a total lifestyle of such communities, in which several other significant lifestyle factors are operative, cannot be expected to show a definitive correlation with disease. Moreover, consumption of soyabean is very low within the Western population and phyto-oestrogen exposure varies substantially across human populations and individuals. Furthermore, Asian diets, which are particularly high in soyabean, result in isoflavone consumption as high as 1 mg/g body weight per d, with plasma isoflavone concentrations reaching 1 μM in Japanese subjects. In Europe circulating levels are usually <0.07 μM for omnivores, and 0.4-0.6 μM-isoflavones and 0.8-1.0 μM-lignans among vegetarians\(^22,23\). Another limitation is the window of exposure\(^24\).

Intervention trials

In adolescents isoflavone supplementation (Novasoy; Archer Daniels Midland Company, Decatur, IL, USA; 50 mg isoflavone equivalents/d) for 6 weeks has been shown to have no measurable effect on bone turnover in adolescent boys\(^25\), even though results from a study of
### Table 1. Epidemiological studies in women

<table>
<thead>
<tr>
<th>Reference</th>
<th>Population</th>
<th>Evaluation of soyabean or isoflavone consumption</th>
<th>Bone health evaluation</th>
<th>Main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaardinaal et al. (64)</td>
<td>Caucasian women, n = 67</td>
<td>Urinary excretion GC–MS</td>
<td>Radial BMD</td>
<td>No difference in urinary excretion of isoflavones for women losing bone at a yearly rate of 0.5% v. 2.5% Urinary concentrations of enterolactone higher in those having the highest rate of osteopenia</td>
</tr>
<tr>
<td>Tsuchida et al. (65)</td>
<td>Japanese middle-aged women, n = 995, age 40–49 years</td>
<td>Self-reporting FFQ</td>
<td>Spine BMD</td>
<td>Independent gradient of non-adjusted and adjusted BMD for age and weekly Ca intake through soyabean-intake frequency (P = 0.03)</td>
</tr>
<tr>
<td>Horiuchi et al. (66)</td>
<td>Japanese women, n = 85, mean age 66-9 (sd 7-4) years</td>
<td>Food weighing over 3 days</td>
<td>Spine and hip BMD</td>
<td>Positive association between soyabean-protein intake (12.6 g/d) and spine BMD Decrease in bone resorption Higher BMD in women with the highest isoflavone intake (tertile 47 mg/d) (P &lt; 0.05) Decrease in both formation and resorption biomarkers (P &lt; 0.05)</td>
</tr>
<tr>
<td>Mei et al. (67)</td>
<td>Chinese women, n = 357, mean age 63 (so 8-3) years</td>
<td>FFQ and interview</td>
<td>Bone turnover biomarkers</td>
<td></td>
</tr>
<tr>
<td>Somekawa et al. (68)</td>
<td>Japanese women, n = 478</td>
<td>FFQ</td>
<td>Spine BMD</td>
<td>Mean consumption 54.3 mg Higher BMD in the highest quartile (P &lt; 0.01)</td>
</tr>
<tr>
<td>Kim et al. (69)</td>
<td>Korean women, n = 75, age 52–65 years</td>
<td>Urinary isoflavone excretion over 24 h (GC–MS)</td>
<td>Spine and femoral BMD</td>
<td>Positive association between enterolactone excretion and spine (P &lt; 0.01) or hip (P &lt; 0.05) BMD Genistein consumption 0–13.9 mg/d Urinary NTX 18% lower in those having the highest intake, compared with those eating less isoflavones (P = 0.09) Trend toward a higher BMD at the spine (P = 0.07) Chinese women: no association between genistein and BMD Premenopausal, but not peri-menopausal, Japanese women whose intakes were greater had higher spine and femoral neck BMD Adjusted mean spinal BMD in the highest tertile of intake was 7.7% greater than that of women in the lowest tertile (P = 0.02); femoral neck BMD was 12% greater in the highest tertile v. the lowest tertile (P &lt; 0.0001)</td>
</tr>
<tr>
<td>Kritz-Silverstein &amp; Goodman-Gruen (70)</td>
<td>Californian women, multiple ethnicity, n = 208, age 47–74 years</td>
<td>FFQ over the previous year</td>
<td>Spine BMD</td>
<td></td>
</tr>
<tr>
<td>Greendale et al. (71)</td>
<td>Baseline data from the Study of Women's Health Across the Nation, a US community-based cohort study of women, age 42–52 years: African-American, n = 497; Caucasian, n = 1003; Chinese, n = 200; Japanese, n = 227</td>
<td></td>
<td>Spine and femoral BMD</td>
<td></td>
</tr>
<tr>
<td>Nagata et al. (72)</td>
<td>Japanese women, n = 87</td>
<td></td>
<td></td>
<td>No relationship with isoflavone consumption (62 g soya foods/d, i.e. 32 mg isoflavones/d)</td>
</tr>
<tr>
<td>Hanna et al. (73)</td>
<td>Australian women, n = 500, age 40–80 years</td>
<td>Phytostrogen-frequency questionnaire (assessment of the intake over the previous month)</td>
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<td></td>
</tr>
</tbody>
</table>
104 Chinese adolescent girls aged 14–16 years indicate that supplementation with 375 ml Ca-fortified soya milk, or an equivalent of about two glasses, can be considered among the effective strategies for bone acquisition and the optimization of peak bone mass in adolescent girls (because the Chinese diet is low in Ca; although this study did not establish which component(s) of the Ca-fortified soya milk (or their combined effect) resulted in the beneficial effect on bone health) (26). In young adult females with normal menses (21–25 years of age) an isoflavone-rich soya preparation (approximately 90 mg total isoflavones/d) has been shown to have no effects on bone mineral content and bone mineral density over a 12-month period(27).

Intervention trials carried out in post-menopausal women are reported in Tables 2 and 3. These studies used either biochemical indices of bone turnover (Table 2) or direct measurements of bone mineral density (Table 3) to examine the effect of soyabean isoflavones ranging from 54 mg to 300 mg/d (most studies used 80–110 mg/d). Evidence from several studies suggests that soyabean proteins and/or their isoflavones may have beneficial effects on bone in post-menopausal women, whereas other trials do not show a benefit over the same or a longer period. Nevertheless, both studies that also targeted Ca have failed to show any significant effect on Ca retention(28,29), despite a 15–20% lower renal acid excretion with the soyabean diet compared with meat (29). Moreover, there is also inconsistency among the studies that show favourable effects, with some finding a benefit in the spine but not the hip and others a benefit in the hip but not the spine.

One study has identified fifteen clinical trials that have examined the effects of isoflavones or isoflavone-rich soyabean protein on bone mineral density (30). Most trials were conducted for ≤1 year and involved relatively few (less than thirty) participants per group. Although the findings from these studies are inconsistent, in general they suggest that isoflavones reduce bone loss in post-menopausal women in the early years following the menopause (<5 years post menopause). Furthermore, two consensus views of soyabean phyto-oestrogens in clinical interventions in post-menopausal women have been published recently; one by the French Food Safety Agency(24) and one from the EU-funded project Phytohealth (31). The comprehensive literature search with well-defined inclusion or exclusion criteria suggests, although there is no conclusive evidence, that isoflavones from the sources studied so far have a beneficial effect on bone health. The health benefits of soyabean phyto-oestrogens in healthy post-menopausal women are subtle and even some well-designed studies do not show protective effects. Both papers conclude that until more definite data are available, soya foods and isoflavones cannot be viewed as substitutes for established anti-osteoporotic medication.

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The varied results of the clinical studies that have been published suggest the need for investigations of the effect of phyto-oestrogens on bone health that have substantial sample size and long duration to provide a definitive result. It has been suggested that the differences may be a result of synergies or antagonisms among the flavones, threshold
Table 2. Intervention trials: effect of soyabean and isoflavones (IF) consumption on bone turnover in women

<table>
<thead>
<tr>
<th>References</th>
<th>Subjects</th>
<th>Type of study</th>
<th>Length of the study (months)</th>
<th>Main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scambia et al.(75)</td>
<td>n 39</td>
<td>IF consumption, 50 mg/d</td>
<td>1.5</td>
<td>No change in osteocalcin</td>
</tr>
<tr>
<td>Wangen et al.(76)</td>
<td>Premenopausal women, n 14; post-menopausal women, n 17</td>
<td>Soyabean proteins containing 8 (controls), 65 or 130 mg IF/d</td>
<td>3</td>
<td>No change in bone turnover</td>
</tr>
<tr>
<td>Upmalis et al.(77)</td>
<td>n 42</td>
<td>Genistein, 50 mg/d</td>
<td>3</td>
<td>No change in osteocalcin and urinary NTX</td>
</tr>
<tr>
<td>Scheiber et al.(78)</td>
<td>n 42</td>
<td>Soya food consumption, i.e. 60 mg IF/d</td>
<td>3</td>
<td>A 13.9% decrease in urinary DPD</td>
</tr>
<tr>
<td>Yamori et al.(79)</td>
<td>Japanese women, n 20</td>
<td>Daily consumption of soyabean germ, i.e. 37.3 mg IF</td>
<td>2.5</td>
<td>Decrease in urinary DPD and pyridinoline compared with the placebo group (n 20)</td>
</tr>
<tr>
<td>Uesugi et al.(80)</td>
<td>Peri-menopausal women, n 23</td>
<td>61.8 mg IF/d</td>
<td>1</td>
<td>Excretion of bone resorption markers was reduced significantly in the IF group</td>
</tr>
<tr>
<td>Lucas et al.(81)</td>
<td>Post-menopausal women</td>
<td>40 g ground flaxseed or wheat-based comparative control regimen daily</td>
<td>3</td>
<td>Markers of bone formation and resorption not affected by either of the treatments</td>
</tr>
<tr>
<td>Arjmandi et al.(82)</td>
<td>n 71</td>
<td>40 g soyabean protein/d</td>
<td>3</td>
<td>Decrease in urinary DPD</td>
</tr>
<tr>
<td>Dalais et al.(83)</td>
<td>Post-menopausal women</td>
<td>110 mg soyabean IF/d</td>
<td>6</td>
<td>No effect on markers for bone resorption (urinary excretion of pyridinoline or deoxypyridinoline)</td>
</tr>
<tr>
<td>Harkness et al.(84)</td>
<td>Post-menopausal women, n 19, mean age 70-6 (or 6-3) years</td>
<td>Cross-over design</td>
<td>One menstrual cycle</td>
<td>A 37% decrease in urinary concentration of type 1 collagen α1-chain helical peptide (a marker for bone resorption)</td>
</tr>
<tr>
<td>Zittermann et al.(85)</td>
<td>Young Caucasian women, n 70, mean age 24-0 (or 0-9) years</td>
<td>Cookies, 52 mg IF/d</td>
<td></td>
<td>IF affect physiological fluctuations in bone turnover (CTX (bone resorption);osteocalcin (bone formation)) was slightly higher during the soyabean period</td>
</tr>
<tr>
<td>Roudsari et al.(86)</td>
<td>Women, n 15, age 45-64 years</td>
<td>35 g soyabean protein/d</td>
<td>3</td>
<td>Reduction in urinary DPD and increased total ALP</td>
</tr>
</tbody>
</table>

NTX, N-terminal cross-linked telopeptides; DPD, deoxypyridinoline; CTX, C-terminal cross-linked telopeptides; ALP, alkaline phosphatase; IGFBP, insulin-like growth factor-binding protein.
or biphasic dose effects, life-stage oestrogen status or environmental interactions, including the ability to produce metabolites on ingestion of isoflavones. Perimenopausal women and women in early menopause may therefore be more receptive to the therapeutic effects of isoflavones before the decrease in ER that occurs in the post-menopausal years. Moreover, the major weakness of previous clinical trials is that the risk of fracture, which is actually the ultimate hallmark of bone quality, was not targeted. However, the relationship between usual soyabean food consumption and fracture incidence has been examined in 24,403 post-menopausal Chinese women (recruited in the Shanghai Women’s Health Study, a cohort study of approximately 75,000 women aged 40–70 years). Evidence was found that soy food consumption may reduce the risk of fracture in these women, particularly among those in the early years following menopause, (after adjustment for confounding factors, the relative risks of fracture were 1.00, 0.72 (95% CI 0.62, 0.83), 0.69 (95% CI 0.59, 0.80), 0.64 (95% CI 0.55, 0.76) and 0.63 (95% CI 0.53, 0.76) across quintiles of soyabean protein intake (P < 0.001 for trend). However, it is questionable whether these data can be extrapolated to the Caucasian population.

Phyto-oestrogen bioavailability and bone health

It has been found that the intestinal metabolism of isoflavones could be the more important clue to the clinical efficacy of soy foods in preventing osteopenia. Indeed, the bioavailability of isoflavones requires an initial hydrolysis of the sugar moiety by intestinal bacterial (Lactobacilli, Bacteroides and Bifidobacteria) β-glucosidases to allow subsequent uptake by enterocytes. Moreover, the final exposure depends on the microbial potential to activate all different groups of phyto-oestrogens within each individual subject. Indeed, phyto-oestrogens (and more especially daidzein) can undergo a further metabolism and be converted into a more potent molecule, equol. However, this bacterial metabolite has been found, on average, in only 45% of the post-menopausal women studied. It has been suggested that individuals can be separated into high, moderate and low O-desmethylandolsen, equol, enterodiol, enterolactone or 8-prenylnaringenin producers, even though the metabolism of isoflavones, lignans and prenylflavonoids follows separate independent pathways. Moreover, enterodiol production correlates negatively with Clostridium coccoides–Exbacterium rectale counts, while O-desmethylandolsen production is associated with the abundance of methanogens, whereas equol production is correlated with sulfate-reducing bacteria.

Equol has a longer half-life and a much higher affinity for the ER than its precursor (daidzein) and has the highest antioxidant capacity among isoflavones. It has been reported that isoflavone treatment in subjects who have the capacity to produce equol differentially affects gene expression as compared with non-producers, supporting the plausibility of the importance of equol production. In general, isoflavones have a stronger effect on some putative oestrogen-responsive genes in equol producers than in non-producers. This finding could explain the results from a 2-year study carried out in post-menopausal women randomized to consume 500 ml soya milk either with or without isoflavones. In this study greater effects on bone health were elicited when volunteers were able to produce equol (a 2.4% increase in lumbar-spine bone mineral density compared with the control group), while no significant difference was shown in non-producers. Similarly, it has been reported that in 128 volunteers classified by equol status (producers or non-producers) the percentage changes in bone mineral density for equol producers are –0.53 and +0.13 in the sub-whole body and total hip respectively, which are significantly different from the corresponding changes of –1.35 and –1.77 in non-producers in the isoflavone group (P = 0.049 and P = 0.040 respectively). However, in another study it was found that total leg and head bone mineral density are greater (6%) in O-desmethylandolsen producers (n = 76) compared with non-producers (n = 16), while total and site-specific bone mineral density are not different in equol producers (n = 24) and non-producers (n = 68). Furthermore, equol has been shown to inhibit bone loss in ovariectomized mice, apparently without oestrogenic activity in the reproductive organs. Hence, substances that can modulate the intestinal microflora could affect equol production. The prebiotic fructo-oligosaccharides have been reported to enhance the effects of soyabean isoflavones on bone mineral density and to reverse the loss of certain microarchitectural variables such as trabecular number, separation and thickness in ovariectomized osteopenic female rats.

Mechanisms of action

Phyto-oestrogens could elicit their bone sparing effect by modulating Ca metabolism, as has been reported for oestrogens. There is evidence that intestinal Ca absorption is higher in ovariectomized rats given soya milk-containing diets than in those receiving a control diet. Nevertheless, it has been shown that ipriflavone, a synthetic phyto-oestrogen-like compound that is similar in structure to the soyabean isoflavone daidzein, increases total Ca transport under low oestrogen conditions, but not under oestrogen-free conditions (via an increased transcellular transport). Moreover, coumestrol or apigenin have no effect on Ca transport.

Phyto-oestrogens can directly modulate bone metabolism. Using a radioactive cDNA microarray to investigate gene expression profiles (1152 genes), it has been shown that genistein treatment in ovariectomized mice modulates bone metabolism-related gene expression, including calciotropic receptor, cytokines, growth factors and bone matrix protein; thirty-eight genes being up regulated (e.g. mitogen-activated protein kinase 10), while eighteen are down regulated (e.g. matrix metalloproteinase 13). Similarly, it has been demonstrated that in hFOB/E199 cells (normal fetal osteoblasts) both genistein and oestradiol increase the endogenous gene expression of the progesterone receptor, the proteoglycan versican and alkaline phosphatase.
Table 3. Intervention trials: effect of soyabean and isoflavones (IF) consumption on bone mineral density in post-menopausal women

<table>
<thead>
<tr>
<th>Reference</th>
<th>Subjects</th>
<th>Type of study</th>
<th>Length of the study</th>
<th>Main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potter et al.</td>
<td>Hypercholesterol, n 66, age 41–83 years</td>
<td>40 g soyabean-protein isolate (90 mg IF)/d</td>
<td>6 months</td>
<td>Increase in BMC and BMD at the spine</td>
</tr>
<tr>
<td>Dalais et al.</td>
<td>n 52, age 45–65 years</td>
<td>Bread containing either 45 g soyabean, linseed or wheat/d</td>
<td>3 months</td>
<td>A 5.2% increase in BMC</td>
</tr>
<tr>
<td>Alekel et al.</td>
<td>n 69, mean age 50-6 years</td>
<td>40 g soyabean protein (80-4 mg IF aglycones)/d</td>
<td>6 months</td>
<td>A 5.6% and 10.1% increase in BMD and BMC respectively at the spine</td>
</tr>
<tr>
<td>Clifton-Bligh et al.</td>
<td>n 46, age &lt; 65 years</td>
<td>28.5, 57 or 85.5 mg IF/d</td>
<td>6 months</td>
<td>Consumption of the two highest doses is associated with a 4.1 and 3.0% increase in BMD at the radius and cubitus level</td>
</tr>
<tr>
<td>Hsu et al.</td>
<td>n 37</td>
<td>150 mg IF/d</td>
<td>6 months</td>
<td>No change in DPD</td>
</tr>
<tr>
<td>Chiechi et al.</td>
<td>n 187</td>
<td>47 mg IF/d</td>
<td>6 months</td>
<td>No change in BMD measured on the calcaneum</td>
</tr>
<tr>
<td>Lydeking-Olsen et al.</td>
<td>n 108</td>
<td>500 ml soya milk (85 mg IF aglycones or depleted in IF (&lt;1 mg))/d</td>
<td>2 years</td>
<td>Increase in plasma osteocalcin</td>
</tr>
<tr>
<td>Vitolins et al.</td>
<td>n 172</td>
<td>25 g soyabean protein (5, 42 or 58 mg IF)</td>
<td>2 years</td>
<td>Protective effect on total BMD, whatever the dose of IF</td>
</tr>
<tr>
<td>Morabito et al.</td>
<td>n 90, age 47–57 years</td>
<td>54 mg genistein/d, HRT or placebo</td>
<td>1 year</td>
<td>Genistein supplementation associated with a decrease in urinary DPD, an increase in biomarkers for osteoblast activity and an increase in spine and hip BMD</td>
</tr>
<tr>
<td>Chen et al.</td>
<td>Chinese population, n 203, age 48–62 years</td>
<td>40 or 80 mg IF/d, 500 mg Ca, 3 μg vitamin D</td>
<td>1 year</td>
<td>Protective effect on BMC at the hip and trochanter with IF</td>
</tr>
<tr>
<td>Gallagher et al.</td>
<td>n 65, age 55–75 years</td>
<td>96 mg IF, 52 g IF or soyabean without IF (&lt;4 mg)/d</td>
<td>9 months</td>
<td>No effect on BMD of the spine or femoral neck in any of the three groups</td>
</tr>
<tr>
<td>Harkness et al.</td>
<td>n 19, mean age 70-6 (sd 6-3) years</td>
<td>110 mg soyabean IF/d</td>
<td>6 months</td>
<td>BMD increased significantly in the trochanter at 9 months (P = 0.02) and at 15 months (P&lt;0.05) in the group given IF-free soyabean compared with the other two groups</td>
</tr>
<tr>
<td>Lydeking-Olsen et al.</td>
<td>Caucasian women with established osteoporosis or at least three risk-factors for osteoporosis, n 89</td>
<td>Soya milk, with or without IF (76 mg/d) with natural transdermal progesterone, a combination or placebo</td>
<td>2 years</td>
<td>Prevention of lumbar spine bone loss (BMD +1.1% v. -4.2% in the control group)</td>
</tr>
<tr>
<td>Kreijkamp-Kaspers et al.</td>
<td>n 202, age 60–75 years</td>
<td>25.6 g soyabean protein containing 99 mg IF</td>
<td>1 year</td>
<td>No effect on BMD (lumbar spine and femur)</td>
</tr>
</tbody>
</table>

Women who had the most recent onset of menopause had better results.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention</th>
<th>Duration</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atkinson et al.</td>
<td>n 177, age 49–65 years</td>
<td>A red clover (Trifolium pratense)-derived IF supplement (daily dose of 26 mg biochanin A, 16 mg formononetin, 1 mg genistein and 0.5 mg daidzein)</td>
<td>1 year</td>
<td>Lower loss of lumbar spine BMC and BMD ($P = 0.04$ and $P = 0.03$, respectively) in the IF group</td>
</tr>
<tr>
<td>Arjmandi et al.</td>
<td>n 62</td>
<td>Soyabean-containing foods providing 25 g protein and 60 mg IF/d</td>
<td>1 year</td>
<td>No significant treatment effects on hip BMC or BMD, markers of bone resorption</td>
</tr>
<tr>
<td>Huang et al.</td>
<td>n 43, age 45–67 years</td>
<td>100 or 200 mg IF/d</td>
<td>1 year</td>
<td>Bone formation markers significantly increased in the intervention group</td>
</tr>
<tr>
<td>Newton et al.</td>
<td>Women, n 13 and men, n 98, age 50–80 years</td>
<td>83 mg IF/d</td>
<td>1 year</td>
<td>No significant change in total hip BMD and BMC irrespective of treatment</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>Japanese women (&lt;5 years after the onset of menopause), n 136</td>
<td>75 mg IF conjugate/d with or without walking exercise (45 min/d, 3 d/week)</td>
<td>12 months</td>
<td>Whole body and lumbar BMD decreased</td>
</tr>
<tr>
<td>Ye et al.</td>
<td>Early post-menopausal Chinese women, n 90, age 45–60 years</td>
<td>0, 84 or 126 mg IF/d</td>
<td>6 months</td>
<td>A significant effect on BMD only at Ward’s triangle</td>
</tr>
</tbody>
</table>

Bone formation markers significantly increased in the intervention group. No significant change in total hip BMD and BMC irrespective of treatment. Whole body and lumbar BMD decreased. Increased alkaline phosphatase, osteocalcin.

HRT, hormone-replacement therapy; BMC, bone mineral content; BMD, bone mineral density; DPD, deoxypyridinoline.
phosphatase, but inhibit osteopontin gene expression and IL-6 protein levels. In fact, both genomic and non-genomic mechanisms have been proposed to explain their effect. They are able to interact with enzymes and receptors and, because of their stable structure and low molecular weight, they can pass through cell membranes. Mechanistically, phyto-oestrogens have been shown to bind to the two types of ER, their relative affinity for ERβ being greater than that for ERα, and may thus produce distinct clinical effects from oestrogens by differentially triggering transcriptional activation or repression pathways via ERβ. Moreover, they can act on both bone cell lineages. It has been reported that phyto-oestrogens such as coumestrol, genistein and daidzein increase alkaline phosphatase activity and enhance bone mineralization in MC3T3-E1 cells (osteoblast-like cell). It has been demonstrated that daidzein stimulates osteoblast differentiation at various stages (from osteoprogenitors to terminally-differentiated osteoblasts). Daidzein induces changes in the actin cytoskeleton responsible for cell adhesion and motility and activates two transcription factors, cAMP-response element-binding protein and Elk1, which are linked to early genes controlling cell proliferation and differentiation via the mitogen-activated protein kinases extracellular signal-regulated kinases 1 and 2. It is also recognized that isoflavones inhibit in vitro bone resorption, via direct targeting of osteoclasts and/or osteoclast progenitors. Certainly, genistein can decrease osteoclast differentiation and increase osteoclast apoptosis or interfere with signalling pathways such as intracellular Ca2+, cAMP or protein kinase and protein tyrosine phosphatase or via inhibition of topoisomerase II activity. Tyrosine kinase inhibition, in turn, has been reported to directly inhibit osteoclast membrane HCl transport. Furthermore, the maturation of osteoclast is dependent on two factors, macrophage colony-stimulating factor and receptor activator of NF-κB-ligand. It has been shown that coumestrol has an inhibitory effect on the differentiation of osteoclasts, at least partially via decreased receptor activator of NF-κB-ligand-induced phosphorylation of extracellular signal-regulated kinases/p44/p42. These data are consistent with other published data. Furthermore, phyto-oestrogens such as genistein are able to enhance osteoblastic osteoprotegerin production through ERα-dependent mechanisms and concurrently suppress receptor activator of NF-κB-ligand gene expression, which is associated with an inhibition of osteoclastogenesis; bone resorption during the remodelling cycle being coupled to bone formation through the receptor activator of NF-κB/receptor activator of NF-κB-ligand/osteoprotegerin system.

Finally, PPAR have recently been identified as additional targets of phyto-oestrogen, which can dose dependently activate PPAR and induce divergent effects on adipogenesis and osteogenesis. Dominant ER-mediated effects (increased osteogenesis and decreased adipogenesis) can only be seen at low concentrations of phyto-oestrogens, whereas dominant PPAR-mediated effects are only evident at high concentrations. Consequently, divergent actions can be produced in the same cell–tissue system.

Conclusion

Continued awareness and promotion of preventive health services relevant to issues of post-menopausal women will certainly contribute to achieving a healthier population. Thus, the use of phyto-oestrogens is receiving great scrutiny for the purpose of both enhancing the health of tissue and preventing several common diseases, including osteoporosis. However, the limits of the information obtained so far must be appreciated and more data is needed before health professionals can actively advocate the increased consumption of such compounds. Indeed, it will be important to further characterize their physiological effects and margins of safety. In targeting bone health the main issue that remains to be resolved is the effect of phyto-oestrogens in terms of bone strength (which is the ultimate hallmark of bone quality).

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