Vitamin D status and its relationship with parathyroid hormone and bone mineral status in older adolescents

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Osteoporosis is an important contributor to the global burden of disease, and in the UK alone results in one in three women and one in twelve men aged >50 years experiencing a fragility fracture. Optimising peak bone mass in early adulthood is thought to reduce osteoporosis risk by offsetting bone losses in later life. Ensuring sufficient vitamin D status (measured as 25-hydroxyvitamin D (25OHD) in plasma), among other factors, is believed to facilitate the achievement of optimum peak bone mass. Lower 25OHD is associated with a higher plasma concentration of parathyroid hormone (PTH). As PTH is associated with increased bone turnover and bone loss, maintenance of sufficient 25OHD is thought to have a protective effect on bone health. However, there is a lack of consensus internationally on what constitutes an optimum 25OHD concentration, and values between 30 and 80 nmol/l have been suggested. These values have been based on findings from various studies in adults in which PTH has been observed to plateau at a 25OHD concentration of >30 nmol/l; however, not all studies have found such a plateau. Although studies in younger adolescents (14–16 years) have shown an inverse relationship between PTH and 25OHD, the concentration of 25OHD required for achievement of optimum peak bone mass is unknown. The present review examines the evidence defining vitamin D insufficiency thresholds, and the relevance of such thresholds to adolescent bone health.

Vitamin D: 25OHD: Adolescence: Peak bone mass: Bone mineral status: Bone turnover

Osteoporosis is a multifactorial progressive skeletal disease characterised by low bone mass and micro-architectural deterioration of bone tissue with a consequent increase in bone fragility and risk of fracture (Consensus Development Conference, 1993). It results in a reduced quality of life and a marked increase in mortality risk (Gilsanz, 1998). Osteoporosis is an important contributor to the global burden of disease and results in >1.6 x 10^6 hip fractures each year (Cooper et al. 1992). In the UK alone one in three women and one in twelve men aged >50 years currently experience a fragility fracture as a result of the condition (National Osteoporosis Society Online, 2004), and the numbers are rising. The estimated annual cost of the treatment of osteoporotic fractures in the UK is £1.7 x 10^9 (Russell et al. 2003). Although osteoporosis is primarily a disease of the elderly, it is believed that the foundations of the condition are laid in childhood and adolescence (Root, 2002). Adolescence is a critical time for bone mineral accrual (Kun et al. 2001), resulting in approximately 90% of peak bone mass being attained by the age of 18 years (Slemenda et al. 1994). Optimising peak bone mass in early adulthood is thought to reduce the risk of osteoporosis by offsetting bone losses later in life.

A multiplicity of interacting endogenous and exogenous factors influence the achievement of peak bone mass (Heaney et al. 2000; Saggese et al. 2001), including genotype (Jouanny et al. 1995; Rubin et al. 1999), physical activity (Fehily et al. 1992; Rubin et al. 1999) and diet (Wang et al. 2003). Furthermore, ensuring a sufficient vitamin D status is also believed to be an important factor for achieving optimal peak bone mass. In the transition from adolescence to adulthood and the cessation of bone growth and mineral accrual it is not known whether variations in vitamin D status result in variations in bone mineral status, and whether there are site-specific effects. The present paper reviews the current definitions of

Abbreviations: BMD, bone mineral density; CBS, Cambridge Bone Studies; 25OHD, 25-hydroxyvitamin D; NDNS, National Diet and Nutrition Survey; PTH, parathyroid hormone.

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vitamin D insufficiency thresholds and explores their relevance to adolescent bone health.

**Bone changes during adolescence**

Adolescence is characterised by changes in height, weight and body composition, and is also a crucial time for bone development and mineralisation (Kun et al. 2001). The attainment of maximum peak bone mass is thought to be an important determinant of osteoporosis, as the mass of bony tissue present at any time during adult life is simply the difference between the amount achieved at maturity and that lost with aging (Bonjour et al. 1994). Adolescents are thus an important demographic group in terms of osteoporosis prevention, and it is clear that efforts should be made to ascertain that adolescents attain 100% of their peak bone mass potential (Cromer & Harel, 2000).

Bone is a metabolically-active tissue that constantly undergoes phases of turnover, involving systemic bone breakdown (resorption) and new formation. If the balance of bone formation to bone resorption is disturbed, over time bone architecture, resistance and elasticity can be adversely affected (Ballabriga, 2000). Two processes comprise bone growth: cortical bone develops by periosteal apposition that widens the bone shaft; the trabecular bone assemblies by endochondral ossification as bones grow in length (Parfitt, 1994). Bone modelling (where a greater rate of bone formation occurs compared with bone resorption) occurs shortly after the growth spurt and is largely replaced by bone remodelling (an equal rate of bone formation and bone resorption). The function of remodelling is to both maintain the structural integrity of the skeleton and subserve its metabolic functions as a store of Ca and P (Raisz, 1999). Various skeletal sites grow at differential rates. For example, growth of the appendicular skeleton (i.e. the limbs) is greater, relative to that of the axial skeleton (such as the spine and hip), before puberty but then decelerates at puberty when axial growth accelerates (Bass et al. 1999; Szulc et al. 2000). The timing of peak bone mass is also variable between skeletal sites (e.g. hip and forearm); because at a given point there may still be bone formation in one skeletal site, relative equilibrium in another and bone loss in a further site; Szulc et al. 2000), between individuals and especially between the genders. Boys generally start puberty at about the age of 14 years, approximately 2 years later than girls, and their pubertal growth spurt lasts for about 4 years compared with 3 years in girls (Riggs et al. 1999). It is thought that these differences between the genders (i.e. prolonged puberty and greater body size) account for the greater peak bone mass in boys (Riggs et al. 1999).

Little is known about environmental determinants of mineral accretion and bone development in the older adolescent age-group. Parsons et al. (1996) have shown that bone mineral is still being accumulated in young adults aged 18–21 years, but lifestyle or anthropometric factors that influenced these bone mineral changes could not be identified. Ginty et al. (2005b) have found a positive association between bone mineral status and daily participation in high-impact physical activity in 16–18-year-old adolescent boys. In another study (Gustavsson et al. 2003) 16–19-year-old adolescent male badminton and ice hockey players have also been found to have a higher bone mineral status than age-matched controls over 3 years.

**Assessment of bone health**

Dual-energy X-ray absorptiometry has become the standard clinical method for the assessment of areal bone mineral density (BMD) at prominent fracture sites, such as the forearm, lumbar spine and femur (Reid, 2003). BMD provides a measurement of the bone mineral content, which is then partially corrected for size by correcting for the area of the bone assessed (Reid, 2003). Bone size, however, can markedly influence BMD, thus adjustment of bone mineral content in multiple regression analysis for bone area, body weight and height, for example, is a useful method of correcting for this confounder (Cole & Prentice, 1992; Prentice, 2004). The issue of size correction is of particular importance when studying subjects who are still growing, e.g. adolescents. There is now widespread agreement that BMD should not be used as a measure of bone mineral status during growth because of changes in bone size, and that bone mineral content should be assessed instead, preferably, if appropriate, with adjustment for body and bone size (Fewtrell, 2003; Heaney, 2003; Prentice, 2004).

Bone turnover can be assessed by the measurement of turnover markers in blood and urine, in which the end products of bone formation or resorption are excreted. Examples of markers of bone formation include osteocalcin and bone-specific alkaline phosphatase, both of which are specific products of osteoblasts (bone-forming cells) and can be measured in blood (Szulc et al. 2000; Woitge & Seibel, 2001). Bone resorption may be measured, for example, by urinary markers such as deoxypyridinoline and N-telopeptides of type I collagen, which form cross-links to stabilise collagen and during bone matrix resorption are released into the circulation and excreted in urine (Szulc et al. 2000).

During adolescence bone turnover is elevated compared with that in adults, consistent with skeletal growth and consolidation. During the pubertal growth spurt bone marker levels are up to four to five times higher than those in adults (Saggese et al. 2002). In older adolescents the biochemical markers of turnover decrease, but they decrease later and more slowly in boys than in girls, because of their later and longer growth spurt (Szulc et al. 2000).

**Vitamin D**

**Vitamin D synthesis**

Vitamin D is the generic descriptor for ergocalciferol (vitamin D$_3$) and cholecalciferol (vitamin D$_2$), and is acquired in man from the diet and by cutaneous synthesis following exposure to sunlight. It is estimated that about 80–90% of the body’s vitamin D requirement is acquired via the skin and the remainder from food sources (Holick, 1999).
During sun exposure UVB photons of light stimulate the conversion of 7-dehydrocholesterol in the skin to pre-cholecalciferol by photolysis (Webb & Holick, 1988; Holick, 1995). The precholecalciferol is then transformed in the epidermis through thermal isomerisation to cholecalciferol. Cholecalciferol selectively (in preference to precholecalciferol) exits the plasma membrane of the skin into the extracellular space by binding to the vitamin D-binding protein in the capillary bed of the epidermis (Holick, 1981). The amount of photoconversion occurring is dependent not only on the appropriate wavelengths of UV light (295–315 nm; Chen et al. 2000) but also on the quantity of UV radiation reaching each layer of the skin (Webb & Holick, 1988).

While the cutaneous pathway for vitamin D synthesis provides the main source of the vitamin, the main dietary sources of ergocalciferol and cholecalciferol in the UK are oily fish, full-fat dairy foods, such as milk, butter and cheese, egg yolk, liver and fortified products such as margarine and cereals (Department of Health, 1998) and are intestinally absorbed. Ergocalciferol or cholecalciferol, as such, are not believed to have important biological activity and are stored in fat deposits in the body (Garrow et al. 2000).

Ergocalciferol and cholecalciferol are transported to the liver with the same relative affinity by vitamin D-binding protein (Norman, 1992; Holick, 1996), which is a multifunctional plasma protein synthesised in the liver that provides a high-affinity high-capacity binding reservoir for, and regulates cellular access of, vitamin D and its metabolites (Haddad, 1999). Within the liver ergocalciferol and cholecalciferol are converted to their corresponding 25-hydroxy derivative by the enzyme 25-hydroxylase. 25-Hydroxyvitamin D (25OHD) is the circulating metabolite of vitamin D and is typically measured as an index of vitamin D status. The half-life of 25OHD has been shown to be approximately 3 weeks (Lund et al. 1980; Holick, 2004).

**Vitamin D requirements**

The level of vitamin D required (whether by cutaneous synthesis or via dietary intake) in order to maintain sufficient plasma 25OHD levels for the achievement of optimal peak bone mass is not known. Holick (1999, 2001) has shown that exposure of 6–10% of the body surface to one minimal erythemal dose of sunlight, defined as enough sun to cause pinkness to the skin (Holick, 2004), is equivalent to ingesting approximately 15–25 μg vitamin D, although the effect on plasma levels of 25OHD was not explored. Hence, exposure of the hands, arms and face two to three times per week to about 0.5 minimal erythemal dose (about 5 min for a skin-type-2 adult in Boston (latitude 42.2° N) at noon in July) in the spring, summer and autumn would, according to Holick (2004), provide adequate exposure.

In terms of dietary intakes of vitamin D the UK reference nutrient intake for at-risk adults, such as pregnant and lactating women, adults >65 years old and individuals with limited sun exposure, is currently 10 μg/d (Department of Health, 1998). However, there is currently no recommended daily intake of vitamin D for adolescents in the UK, as it has been considered that they will generally achieve an adequate amount from normal exposure to sunlight (Department of Health, 1998). In France and the USA vitamin D intake recommendations have been made, and the recommended intake is 10 μg/d for 15–18 year olds (Department of Health, 1998).

**Determinants of vitamin D status**

**Season and sunlight exposure**

25OHD has been consistently demonstrated to be markedly lower during the winter months than during the summer months in studies of adolescents from various temperate countries, including China (Du et al. 2001), France (Guillemant et al. 1999), Finland (Lehtónen-Veromaa et al. 1999; Outila et al. 2001), Lebanon (El-Hajj Fuleihan et al. 2001) and the UK (Ellis et al. 1977). Generally, this seasonal variation in 25OHD is apparent in countries at a distance from the equator because less time is spent outdoors in winter and because 25OHD is not synthesised from UVB exposure during the winter months. In the UK National Diet and Nutrition Survey (NDNS; Gregory & Lowe, 2000) 25OHD levels for both boys and girls (11–18 years old) were found to be markedly higher when measured during the summer study wave (July–September) than at other times of the year. Similarly, in 116 boys and 109 girls (aged 16–18 years) from the Cambridge Bone Studies (CBS; Stear et al. 2003) 25OHD levels during the winter (January–March) were observed to be significantly lower than those during the autumn (September to January) in both boys (33·3 (sd 12·8) nmol/l v. 49·6 (sd 16·6) nmol/l respectively, \(P < 0·0001\); Willett et al. 2005a) and girls (38·8 (sd 14·0) v. 53·4 (sd 14·7) nmol/l respectively, \(P < 0·0001\); Willett et al. 2004).

**Diet: vitamin D**

At northern latitudes during the winter months cutaneous synthesis of vitamin D is limited, and dietary and supplementary sources of vitamin D may be important to maintain a sufficient 25OHD status and avoid prolonged elevated PTH concentrations. It has also been suggested that while winter sunlight cannot produce vitamin D in the skin, it may actually promote the photo-degradation of nutritionally-obtained vitamin D (Webb et al. 1989). It is thought that UV light exposure during the winter can photoisomerise cholecalciferol, thus causing its destruction (Webb et al. 1989). The UVB wavelengths responsible for this photodestruction are longer, with lower energy radiation (316–330 nm), than those that synthesise cutaneous vitamin D, but unlike the latter wavelengths they are present all year round. It is thought that in summer months these longer wavelengths help to prevent vitamin D toxicity via their catabolic mechanism; however, during the winter it is proposed that this mechanism may lead to decreasing vitamin D and, subsequently, 25OHD levels (Webb et al. 1989).
Data from 298 11–18-year-old boys in the NDNS has shown that during the winter study wave (January–March) 25OHD is significantly positively associated (P < 0.01) with dietary vitamin D intake (Willett, 2004). A similar association has also been found in 16–18-year-old boys from the CBS (Willett et al. 2005b). Furthermore, a positive relationship between 25OHD and vitamin D intake has been reported for UK preschool children during the winter (Davies et al. 1999), and for elderly subjects in the UK NDNS in the autumn, winter and spring but not the summer (Bates et al. 2003). It is possible that dietary intakes of vitamin D have the most marked impact when cutaneous synthesis of the vitamin is limited and 25OHD stores are low, i.e. during the winter. The intakes of vitamin D in the boys (3.1 (sd 1.7) μg/d) in the CBS are close to the average intake by adults in the UK (Pryme et al. 2004). It is surprising that these relatively low intakes of vitamin D should have a marked impact on 25OHD, especially considering the frequent lack of effect seen with vitamin D supplementation at much higher doses (discussed later; see this page).

Vitamin D supplements

Vitamin D supplementation studies have been carried out in an attempt to quantify the effects of known levels of vitamin D intake on 25OHD. Heaney et al. (2003) have found that 1μg cholecalciferol leads to a 0.7 nmol/l increase in winter circulating levels of 25OHD in men (mean age 38.7 (sd 11.2) years), and have estimated that to sustain autumn concentrations of 25OHD a total of approximately 96μg is needed, with about 12.5μg of this amount being supplied from oral sources. Thus, typical vitamin D intakes in healthy men are too low to maintain desirable 25OHD levels (i.e. their post-summer levels). However, most vitamin D supplementation studies have been carried out in elderly populations and the results have been variable; both positive effects (Chapuy et al. 2002) and no effects (Patel et al. 2001; Meyer et al. 2002) have been reported. Such variation could be attributable to methodological differences in the type of assay and kit used to quantify 25OHD, and their affinities for ergocalciferol and cholecalciferol (discussed further on p. 197).

Few vitamin D supplementation studies have been conducted in adolescents. Lehtonen-Veromaa et al. (1999) have carried out one study in 9–15-year-old Finnish girls (n 191) monitored over the course of 12 months. After 6 months all subjects were supplemented for 3 months with a multivitamin containing 10μg vitamin D. Despite the 93.4% compliance with the supplementation, the final 25OHD concentrations were found to be as low as the baseline concentrations. It was concluded that the dose of vitamin D supplementation given to the subjects was too low to maintain a sufficient 25OHD for optimal bone mineral accrual in Finland. However, vitamin D supplementation was discontinued 1 month before the final sample collection, which, given the 3-week half-life of 25OHD, may account for the relative lack of change from the baseline 25OHD concentration.

A study carried out by Guilemant et al. (2001) has demonstrated that a 2.5mg oral dose of cholecalciferol, administered every 2 months for 6 months is sufficient to maintain the concentrations of both 25OHD and PTH at their baseline post-summer levels. While a marked decrease in serum 25OHD values was observed from summer to winter in the control group, the mean 25OHD concentrations in the supplemented subjects were found to show little change. The Guilemant et al. (2001) study provided approximately four times the dose of the Lehtonen-Veromaa et al. (1999) study, suggesting that this level is more likely to be effective in maintaining 25OHD levels. However, the physiological effects of the dose used (2.5mg cholecalciferol administered orally every 2 months) are unclear.

Of the boys in the CBS current supplement users were found to have higher 25OHD levels during winter (Willett, 2004). However, despite the correlation with supplement use, no relationship was found between the supplement type (e.g. multivitamin, cod liver oil) and contents (i.e. constituent vitamins and minerals) and 25OHD, although it was noted that 62.2% of the supplement users took supplements (cod liver oil and multivitamins) that contained vitamin D. This positive association between 25OHD and the use of supplements may thus merely reflect a greater personal interest in health by the subjects who took the supplements, rather than a biological effect of the supplements.

Ethnic group

Research has shown that 25OHD concentration can be related to the ethnic group of the individual. A negative relationship has been demonstrated between 25OHD concentration and the natural pigmentation of the skin, and it is well recognised that certain ethnic groups are at greater risk of developing 25OHD deficiency and, subsequently, osteomalacia and rickets (Harris & Dawson-Hughes, 1998; Lawson et al. 1999). In ethnic groups with increased melanin a lower 25OHD status has been found, e.g. in populations of Asian origin (O’Hare et al. 1984; Awumey et al. 1998; Lawson et al. 1999) and in those of African-American origin (Harris & Dawson-Hughes, 1998). As melanin functions as a UV light filter, it determines the amount of UVB photons that are able to penetrate the skin (Norman, 1998). The underlying mechanism has yet to be fully elucidated, although it has been shown that melanin absorbs UVB photons in competition with 7-dehydrocholesterol, thus reducing the capacity for vitamin D production (Holicck, 1995). Cultural differences, such as diet and clothing choices, may also influence 25OHD status. Asian populations are known to consume chapattis, for example, which have a high phytate content (thought to interfere with the entero-hepatic circulation of vitamin D metabolites; Clemens, 1989), and often have vegetarian diets, thus limiting their vitamin D intake from animal sources. In some ethnic groups the clothing worn almost completely covers the body, so reducing exposure to UVB light. It is often found, therefore, that non-Caucasian populations, such as Asian Indians (Awumey et al. 1998; Hampson et al. 2003), young American black women...
(Harris & Dawson-Hughes, 1998) and Mexican-American girls (Abrams et al. 1999) have lower 25OHD levels than their Caucasian counterparts (Awumey et al. & Dawson-Hughes, 1998; Abrams et al. & Dawson-Hughes, 1998; Harris & Dawson-Hughes, 1998). Also, the 25OHD levels for the 11–18-year-old subjects from the NDNS are significantly higher for both the Caucasian boys ($P < 0.0001$) and girls ($P < 0.0001$; Willett, 2004) compared with the other ethnic groups (categorised as: black Caribbean; black African; black neither Caribbean or African; Indian; Pakistani; Bangladeshi; Chinese; none of these, including mixed race) in all seasonal study waves. Similarly, in the CBS, the Caucasian boys have a significantly higher 25OHD status at all time points of the year than subjects self-categorised as Asian, Black, Indian or Oriental ($P < 0.0001$; Willett, 2004).

**Age**

25OHD status is thought to change with age, but the evidence thus far is contradictory. Studies that have been undertaken have generally been in adult populations, and less information is available for younger subjects. In several studies of adult populations no significant relationship between 25OHD levels and age has been demonstrated (Sherman et al. 1990; Burnd et al. 1992; Nakamura et al. 2000; Margiloff et al. 2001). However, while some research has found a negative correlation between 25OHD levels and age in elderly subjects $>$65 years old (Dawson-Hughes et al. 1997; Jacques et al. 1997), a study of relatively younger Finnish adults (30–42 years old) has found a positive relationship between 25OHD levels and age (Lamberg-Allardt et al. 2001).

Currently, little is known about the effects of puberty on 25OHD. In a study of Finnish children aged 2–17 years (Ala-Houhala et al. 1984) the 11–17 year olds were found to have a lower 25OHD status than the younger children, but in a study of Lebanese children aged 10–16 years (El-Hajj Fuleihan et al. 2001) no significant association between 25OHD levels and age was found. In the NDNS (Gregory & Lowe, 2000) it was shown that older teenage boys and girls (15–18 years old) have a significantly lower 25OHD status than younger children (4–6 years old). The 25OHD levels for the 11–18-year-old boys from NDNS were found to show a downward trend (non-significant) with age. However, in a further analysis 25OHD values for boys aged 11–12 years were found to be significantly higher than those for boys aged 16–18 years ($P = 0.02$; Willett, 2004). No such association between 25OHD and age was found in 11–18-year-old girls. A comparable decline in 25OHD levels in boys has been reported for Swiss adolescents, with 25OHD levels being lowest in the most-pubertally-advanced boys (Tanner stage 4–5; see Tanner, 1962) compared with those who were less mature (Ginty et al. 2005a). In the NDNS it was found that the amount of physical activity (h) decreases with age in both boys and girls (Gregory & Lowe, 2000), and that 16–18-year-old boys undertake significantly less physical activity (h/d) than the younger age-groups ($P = 0.0002$; Willett, 2004), which may correspond to less time outdoors and, subsequently, less sun exposure.

**Vitamin D insufficiency**

Vitamin D status is conventionally measured as 25OHD concentration in the plasma. The optimum 25OHD concentration for bone health in different age-groups has not been established, and the issue of defining insufficiency thresholds is internationally controversial. The problem of defining vitamin D insufficiency is further compounded by the range of methods used to measure 25OHD, including RIA, HPLC, competitive protein binding assays and ELISA. The results obtained with these methods do not necessarily closely agree. Lips et al. (1999) have undertaken a cross-comparison of the methods used for measuring 25OHD levels and have found that the competitive protein binding assay provides a 25OHD value that is 80% higher than that obtained by HPLC, with the RIA giving intermediate results. Binkley et al. (2004) have found substantial variation in assay performance in a test of 25OHD measurements across laboratories and have called for method standardisation. The Vitamin D External Quality Assessment Scheme has monitored the performance of nine methods for 25OHD measurement from approximately 125 laboratories across many countries, and marked variation has been found across groups and assays (Vieth & Carter, 2001). For example, a difference in measurements of $\leq 22\%$ has been found across groups using the Immunodiagnostic Systems Ltd (Boldon, Tyne & Wear, UK) RIA and a difference of $\leq 25\%$ for the DiaSorin Inc. (Stillwater, MN, USA) RIA. It is therefore apparent that comparisons across studies may be confounded by differing methods of 25OHD measurement.

**Approaches for defining 25-hydroxyvitamin D insufficiency thresholds**

25OHD insufficiency thresholds have often been suggested that are based on the inverse association between PTH and 25OHD. The hypothesis underlying the application of this threshold is that since PTH is associated with increased bone turnover (Department of Health, 1998) and greater bone loss, maintenance of a sufficient concentration of 25OHD is believed to have a protective effect on bone health.

PTH secretion increases in response to a reduction in plasma Ca concentration (Holick, 1996), either as a result of low Ca intake or possibly increased urinary Ca losses or other pathological states. When the body is in a state of hypocalcaemia (Fig. 1) the parathyroid glands are stimulated to increase the synthesis and secretion of PTH (Holick, 1996), which is a major regulator of Ca metabolism and bone turnover (Gonzalez & Martin, 1998). The production of PTH is regulated by the extracellular Ca concentration acting, via the plasma membrane Ca-sensing receptor, on the secretory cells (Vander et al. 2001). In addition to increasing the reabsorption of Ca in the kidney (Holick, 1996), PTH promotes the synthesis of 1α-hydroxylase in the kidney which hydroxylates C-1 of 25OHD to form 1,25-dihydroxyvitamin D (Fraser, 1994). 1,25-Dihydroxyvitamin D is 500–1000 times more biologically active than its precursor, 25OHD (Norman, 1992).
Both PTH and 1,25-dihydroxyvitamin D mobilise monocytic stem cells to become osteoclasts and increase bone resorption, thus releasing Ca into the circulation (Holick, 1996). 1,25-Dihydroxyvitamin D also increases the efficiency of intestinal Ca absorption, by up regulating active transport, and aids the reabsorption of Ca in the kidney. The net effect is to raise the serum Ca concentration and reduce PTH synthesis and secretion from the parathyroid glands (Holick, 1996). In a negative feedback reaction 1,25-dihydroxyvitamin D also suppresses PTH production (Holick, 1996). The effects of 25OHD on PTH secretion are believed to be indirect, whereby low 25OHD may limit intestinal Ca absorption, resulting in decreased plasma Ca.

It has been hypothesised that persistently low 25OHD may result in prolonged elevation of PTH and a subsequent increase in bone resorption. Previously, a 25OHD level above those found in rickets and osteomalacia (Department of Health, 1998). More recently, many thresholds for 25OHD insufficiency have been proposed on the basis of the inverse relationship between PTH and 25OHD. However, there is a lack of consensus on what constitutes an optimum 25OHD concentration, and values between 30 and 80 nmol/l have been suggested (Fig. 2). These values have been based on findings from a number of studies of elderly men and women in which PTH has been observed to plateau at a 25OHD concentration of >30 nmol/l (Salamone et al. 1993; Chapuy et al. 1997; Malabanan et al. 1998); however, not all studies have found such a plateau (Bates et al. 2003). In a study of Canadian men and women from different age-groups (Vieth et al. 2003) the relationship between PTH and 25OHD was not found to show a plateau. Although studies in younger adolescents aged 14–16 years have shown an inverse relationship between PTH and 25OHD status (Outila et al. 2001), the concentration of 25OHD required for achievement of optimum peak bone mass has not been established. In the NDNS low 25OHD levels were found to be common in 11–18 year olds, and the prevalence of low values increased with age, particularly in boys. When analysing 25OHD levels from all the seasonal study waves in these subjects it was found that 11% of the 11–14-year-old boys had 25OHD levels <25 nmol/l (Gregory & Lowe, 2000). In the CBS 19.4% of the girls and 32.2% of the boys aged 16–18 years (n 225) were found to have 25OHD values <25 nmol/l in winter (Willett, 2004). When using higher previously-defined 25OHD thresholds of, for example, <37.5 and <50 nmol/l (Malabanan et al. 1998; Thomas et al. 1998) the percentages increase to 49.1 and 78.7% of the girls and 67.8 and 92.2% of the boys respectively below these thresholds in winter. It is clear that the prevalence of low 25OHD is marked in adolescents, particularly older adolescents, but that the assessment of insufficiency varies greatly depending on the threshold applied.

Many studies have been published to date that report the prevalence of 25OHD insufficiency in their adolescent populations using adult cut-offs (Ala-Houhala et al. 1984;
O’Hare et al. 1984; Lehtönen-Veromaa et al. 1999; Du et al. 2001; El-Hajj Fuleihan et al. 2001; Looker et al. 2002). However, it is not known whether it is appropriate to use such thresholds, given the obvious physiological differences relative to the populations from which the thresholds have been derived. It has been suggested that different mechanisms regulate the secretion of PTH during adolescence as compared with adults (Guillemant et al. 1995). Elevated PTH concentrations may not be driven by the same mechanism in adolescents as in adults, and may not necessarily be detrimental to bone health; concentrations are normally raised during this time (Krabbe et al. 1982; Cadogan et al. 1998) as the rate of bone remodelling and consolidation is at a peak. Furthermore, it is not known whether suppressing PTH, and subsequently bone turnover, should be an aim within this population group, as it would be in adult studies, because raised bone turnover is an essential maturation process during this life stage. Inverse relationships between PTH and 25OHD levels have been found in both the 16–18-year-old boys and girls in the CBS, but the association occurs only during winter (Willett, 2004). The average Ca intakes of the adolescents in the CBS suggest that their serum Ca levels will not be compromised, thus avoiding further elevation of PTH. Thus, a sufficient 25OHD status may be more important in subjects with a low Ca intake. Furthermore, as a plateau was not evident, an insufficiency threshold cannot be easily identified in adolescents.

The ongoing difficulties and controversy associated with the relationship between PTH and 25OHD imply that this approach is not the best way to identify vitamin D sufficiency in populations. New approaches to this problem, potentially beyond the PTH–25OHD axis, should be sought.

Effects of vitamin D status on bone health

Ultimately, the importance of vitamin D status lies in its potential impact on bone health and, within adolescents, its possible association with optimum peak bone mass. Bone mineral status has been found to be positively associated with 25OHD in adults. For example, a positive association between femoral neck BMD (Scharla et al. 1995) and bone strength (Nakamura et al. 2001) and 25OHD has been shown. Furthermore, vitamin D supplementation treatment for 25OHD insufficiency in 229 older men and women, which led to a marked rise in 25OHD, resulted in marked increases in spine and hip BMD (Kantorovich et al. 2000). However, not all studies in adults have found an association between bone mineral status and 25OHD (Sigurdsson et al. 2000; Patel et al. 2001). Fracture rates have also been used as an outcome in assessing the effect of vitamin D on bone health. Positive associations between reduced fracture rates and both dietary and supplemental vitamin D have been found (Chapuy et al. 1992; Feskanich et al. 2003; Trivedi et al. 2003). Limited studies in adults have also demonstrated an inverse correlation between bone turnover markers and 25OHD (Woitge et al. 1998; Jesudason et al. 2002).

In adolescents the association between bone health variables and 25OHD is less clear and the evidence is often conflicting. A number of studies in adolescents have observed a positive effect of 25OHD on forearm BMD (Outila et al. 2001) and lumbar spine BMD (Lehtönen-Veromaa et al. 2002). An association between forearm BMD and 25OHD concentration has been found in a study of 14–16-year-old Finnish girls (Outila et al. 2001). However, the association between BMD and 25OHD was only found in subjects with a 25OHD concentration < 40 nmol/l, and a significant correlation between BMD and PTH was not found. A positive association between lumbar spine BMD after 3 years from baseline and baseline 25OHD concentration has been reported in 9–15-year-old Finnish girls (Lehtönen-Veromaa et al. 2002). However, the subject group included gymnasts and athletes, whose types of physical activity may have affected their bone mineral status differently from controls; only time spent on activity was adjusted for in the analysis. Furthermore, as mentioned earlier, the use of BMD is not uniformly accepted as an accurate measure of bone mineral accretion in growing subjects.

The lack of an association between 25OHD concentration and bone turnover markers (El-Hajj Fuleihan et al. 2001) or bone mineral status (Kristinsson et al. 1998; Oliveri et al. 2000) has been noted in other studies of children and young adults. In 10–16-year-old Lebanese schoolchildren no significant association was found between 25OHD and the bone turnover markers osteocalcin and bone-specific alkaline phosphatase, even though 52% of the subjects were categorised as vitamin D insufficiency (defined as a 25OHD concentration between 25 and 50 nmol/l; El-Hajj Fuleihan et al. 2001). Furthermore, the absence of a significant association between bone resorption marker serum C-terminal telopeptide of type I collagen and bone formation marker N-terminal propeptide of type I procollagen and 25OHD has been noted in 11–16-year-old Swiss boys and girls (Ginty et al. 2005a). In the boys and girls in the CBS no significant association has been found between plasma markers of bone formation (osteocalcin, bone-specific alkaline phosphatase) and urinary resorption markers (N-terminal telopeptide of type I collagen and deoxypyridinoline/creatinine) and baseline 25OHD (Willett et al. 2005b), change in 25OHD or average 25OHD across the study, after adjusting for confounders (Willett, 2004). The relationship between bone mineral content size-adjusted bone mineral content or BMD and 25OHD has also been assessed at the whole body, lumbar vertebrae 1–4, forearm and hip. Some significant positive associations have been found between bone mineral status and 25OHD in the CBS subjects, particularly at the hip, but these associations are largely diminished after size-adjustment (Willett, 2004).

The limited number of established associations between 25OHD and indices of bone health may illustrate the strong confounding effect of puberty on skeletal modelling and remodelling, and that plasma Ca and phosphate concentrations are regulated by factors that are not dependent on 25OHD (Kristinsson et al. 1998). In addition, it has been proposed that it is also possible that summer levels of 25OHD may compensate for wintertime deficiencies and,
therefore, that no overall change in bone health is seen (Oliveri et al. 2000).

It has also been suggested that during adolescence markers of bone turnover offer limited information, as they are better correlated with rates of linear growth than actual bone mineral accrual (Szulc et al. 2000). In addition, these markers are highly variable between individuals, and their concentrations can depend on the amount of marker secreted during bone formation and released from bone during bone resorption, on the catabolism of the marker, on variation associated with circadian rhythms, on the specificity of the marker for bone and on the specificity and precision of assays (Szulc et al. 2000).

Conclusions

Vitamin D insufficiency appears to be an important health issue in adolescents, although the optimum 25OHD level that needs to be maintained remains uncertain. In adolescents the CBS adolescents few significant relationships between 25OHD and indices of bone health persist after adjustment for body size. The effect of 25OHD on bone health in this population group remains unknown and may be confounded by stronger physiological influences of puberty. Further studies are needed in order to fully understand the relationship between PTH and 25OHD in older adolescents. Exploring greater numbers of subjects, longitudinally, with wider ranges of 25OHD levels and Ca intakes may help to clarify the nature of this relationship. Furthermore, ways of identifying insufficiency beyond the PTH–25OHD axis are also required. Adolescents are an important yet complex population group and it is suggested that they are considered in their own right, as mechanisms during this period appear to be different from those in children or adults. The work reported provides a further insight into the determinants of 25OHD in older adolescents and will contribute to the debate on the relative importance of 25OHD for achievement of optimum peak bone mass and osteoporosis prevention.

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