

## The case against ergocalciferol (vitamin D<sub>2</sub>) as a vitamin supplement<sup>1,2</sup>

Lisa A Houghton and Reinhold Vieth

### ABSTRACT

Supplemental vitamin D is available in 2 distinct forms: ergocalciferol (vitamin D<sub>2</sub>) and cholecalciferol (vitamin D<sub>3</sub>). Pharmacopoeias have officially regarded these 2 forms as equivalent and interchangeable, yet this presumption of equivalence is based on studies of rickets prevention in infants conducted 70 y ago. The emergence of 25-hydroxyvitamin D as a measure of vitamin D status provides an objective, quantitative measure of the biological response to vitamin D administration. As a result, vitamin D<sub>3</sub> has proven to be the more potent form of vitamin D in all primate species, including humans. Despite an emerging body of evidence suggesting several plausible explanations for the greater bioefficacy of vitamin D<sub>3</sub>, the form of vitamin D used in major preparations of prescriptions in North America is vitamin D<sub>2</sub>. The case that vitamin D<sub>2</sub> should no longer be considered equivalent to vitamin D<sub>3</sub> is based on differences in their efficacy at raising serum 25-hydroxyvitamin D, diminished binding of vitamin D<sub>2</sub> metabolites to vitamin D binding protein in plasma, and a nonphysiologic metabolism and shorter shelf life of vitamin D<sub>2</sub>. Vitamin D<sub>2</sub>, or ergocalciferol, should not be regarded as a nutrient suitable for supplementation or fortification. *Am J Clin Nutr* 2006;84:694–7.

**KEY WORDS** Vitamin D<sub>2</sub>, vitamin D<sub>3</sub>, ergocalciferol, cholecalciferol, vitamin supplement

### INTRODUCTION

Vitamin D is available in 2 distinct forms, ergocalciferol (vitamin D<sub>2</sub>) and cholecalciferol (vitamin D<sub>3</sub>). These are officially regarded as equivalent and interchangeable (1–3). Although sunshine exposure and fish consumption provide vitamin D in the form of D<sub>3</sub>, a different bioactive, plant-derived form of vitamin D, named vitamin D<sub>2</sub>, was produced in the early 1920s through ultraviolet exposure of foods. This process was patented and licensed to pharmaceutical companies, which led to the development of a medicinal preparation of vitamin D<sub>2</sub> called Viosterol (4). Because antirachitic bioassays were used to establish “rat units” for vitamin D (ie, the amount of vitamin D required for recalcification of the epiphyseal end of tibiae in rats), early workers found it extremely difficult to distinguish between the specific biological value of the 2 forms.

To this day, the major preparations of vitamin D for prescription use in North America are in the form of vitamin D<sub>2</sub>, not

vitamin D<sub>3</sub>. Multivitamins may contain either vitamin D<sub>2</sub> or vitamin D<sub>3</sub>, but most companies are now reformulating their products to contain vitamin D in the D<sub>3</sub> form. Here, we present the case that vitamin D<sub>2</sub> should no longer be considered equivalent to vitamin D<sub>3</sub> and that vitamin D<sub>2</sub>, or ergocalciferol, should not be regarded as a nutrient suitable for supplementation or fortification.

### INCORRECT PRESUMPTION OF VITAMIN D<sub>2</sub> AND D<sub>3</sub> EQUIVALENCE

Assumptions about the equivalency of the 2 forms of vitamin D were questioned shortly after the discovery of vitamin D<sub>2</sub>. As early as 1930, Hess et al (5) suggested that the activity of cod liver oil (vitamin D<sub>3</sub>) and Viosterol (vitamin D<sub>2</sub>) used in the treatment of rickets may have different biologic values. They found that one unit of cod liver oil could be as effective in preventing rickets as 4 units of Viosterol. Over the next 10 y, more than 40 studies were conducted to determine whether the 2 distinct forms of vitamin D were equally effective. The results from these studies were confusing, and, in 1940, Park (6) noted that the work done was of poor quality, making a comparison of the 2 forms exceedingly difficult. Despite these misgivings, Park stated that any effect due to differences between the 2 forms would be minimal and concluded that, “For practical purposes, the vitamin D in Viosterol (vitamin D<sub>2</sub>) may be regarded as being equal to the vitamin D of cod liver oil (vitamin D<sub>3</sub>)” (6). As a result, the World Health Organization recommended in 1949 that 1 IU vitamin D be equivalent to 25 ng crystalline vitamin D<sub>3</sub>, and no distinction was made between vitamin D<sub>2</sub> and vitamin D<sub>3</sub> (7). Shortly thereafter in Germany in the 1950s, formulations of vitamin D<sub>3</sub> were found to be ≈4 times as potent per unit mass as were formulations of vitamin D<sub>2</sub>. Vigantol oil (Merck KGaA, Darmstadt, Germany),

<sup>1</sup> From the School of Nutrition and Dietetics, Acadia University, Wolfville, Canada (LAH); the Department of Nutritional Sciences, University of Toronto, Toronto, Canada (RV); and the Mount Sinai Hospital, Toronto, Canada (RV).

<sup>2</sup> Reprints not available. Address correspondence to L Houghton, School of Nutrition and Dietetics, Acadia University, 12 University Avenue, Wolfville, Nova Scotia, Canada B4P 2R6. E-mail: lisa.houghton@acadiau.ca.

Received January 11, 2006.

Accepted for publication May 5, 2006.

the most popular vitamin D supplement in Europe, was reformulated to replace its vitamin D<sub>2</sub> content with vitamin D<sub>3</sub> (8).

Sustained advancement in the characterization and metabolism of vitamin D and its metabolites led to the proposed recommendation in 1972 that 1 IU vitamin D be defined in moles or molecules rather than in weight terms. Subsequently, both vitamin D<sub>2</sub> and vitamin D<sub>3</sub> were defined to be 65 pmol, such that 1 IU vitamin D<sub>3</sub> (molecular weight: 384) and vitamin D<sub>2</sub> (molecular weight: 396) would be equivalent to 25 ng and 25.78 ng, respectively (9). Nevertheless, almost a half century later, British and American pharmacopoeias continue to generalize the 2 nutritional forms of vitamin D with the simple conversion of gram quantity, where 1 IU of either vitamin D<sub>2</sub> or vitamin D<sub>3</sub> equals 25 ng (1, 3).

Despite early evidence of differences in potency between the 2 vitamin D forms on a per weight basis, it must be highlighted that the widely practiced addition of vitamin D<sub>2</sub> to milk in the United States and Europe in the 1930s served to successfully eradicate rickets as a significant health problem. Additionally, fortification of milk with either vitamin D<sub>2</sub> or vitamin D<sub>3</sub> to this day has proven effective in the elimination of infantile rickets in North America. To prevent infantile rickets, a minimal intake of 2.5 μg (100 IU) vitamin D/d in infants with little sun exposure was shown to be efficacious (10). Thus, despite potential differences in the dose equivalence of vitamin D<sub>2</sub> and D<sub>3</sub>, it is likely that vitamin D<sub>2</sub> is currently provided at a high enough dose per kg infant body weight to maintain adequate bone mineral metabolism. However, compared with the use of cruder markers (ie, rickets or "units equivalence" of the bioassays shown by the older rat data), the use of serum 25-hydroxyvitamin D [25(OH)D] as an objective and quantitative marker of nutritional adequacy has consistently shown specific differences in the biological response of the 2 nutritional vitamin D forms.

The use of 25(OH)D as a biomarker in nonhuman species such as birds showed vitamin D<sub>2</sub> to be only one-tenth as effective as vitamin D<sub>3</sub> at increasing 25(OH)D (11). Likewise, in monkeys, the concentrations of serum 25(OH)D maintained after intake of vitamin D<sub>3</sub> were ≈2- to 3-fold those maintained with comparable amounts of vitamin D<sub>2</sub> (12). In rats, however, vitamin D<sub>2</sub> was found to be more effective (13). These differences have been largely explained on the basis of the relative binding affinity of vitamin D and its metabolites to the plasma vitamin D binding protein (DBP) (14, 15). The weaker binding affinity of vitamin D<sub>2</sub> metabolites to DBP would lead to a shorter circulating half-life and an increased rate of clearance from circulation. Thus, in the case of birds and monkeys, the 25(OH)D<sub>2</sub> metabolite is likely less able to compete for binding sites on DBP. This difference in the binding ability is potentially explained by the presence of a methyl group at carbon 24 on the D<sub>2</sub> molecule (14).

In humans, vitamin D<sub>3</sub> is more effective than vitamin D<sub>2</sub> at raising serum 25(OH)D concentrations. Although previous studies that compared the 2 versions of vitamin D indicated a greater effect of vitamin D<sub>3</sub> on raising 25(OH)D concentrations, evaluation of potency was inconclusive due to the effects of confounding variables (eg, seasonal solar exposure), insufficient sample size, or both (16–18). In an effort to resolve the uncertainties of earlier work, Trang et al (19) compared the ability of an equal molar dose of vitamin D<sub>2</sub> or D<sub>3</sub> (≈100 μg, or 4000 IU) to elevate serum 25(OH)D over 2 wk between February and early May, when vitamin D concentrations and solar exposure are minimal.

Both vitamin D<sub>2</sub> and vitamin D<sub>3</sub> increased serum 25(OH)D concentrations, yet the increase in 25(OH)D was found to be 70% greater (1.70 times) with vitamin D<sub>3</sub> than the increase obtained with vitamin D<sub>2</sub>. When adjusted for concomitant changes in an untreated group, the difference between the 2 groups was ≈2-fold. To further complement these findings, a 3-mo supplementation study by Mastaglia et al (20) found that a dose of 250 μg vitamin D<sub>2</sub>/d (2.5-fold) was needed to achieve similar serum 25(OH)D concentrations to those of the later study using a dose of 100 μg vitamin D<sub>3</sub>/d.

A comparison of the time course of serum 25(OH)D over a period of 28 d after a single dose of either vitamin D<sub>2</sub> or vitamin D<sub>3</sub> (2000 μg, or 50 000 IU, for both) was conducted by Armas et al (21). Both forms of vitamin D produced similar rises in serum 25(OH)D concentration over the first 3 d, suggesting comparable absorption of the 2 forms. In the vitamin D<sub>2</sub>-treated subjects, serum 25(OH)D concentrations fell rapidly, reaching baseline values by day 14. Interestingly, 25(OH)D concentrations then continued to decline in this group and fell below baseline values by day 28. In the D<sub>3</sub>-treated subjects, 25(OH)D continued to rise, peaking by day 14 and remaining above baseline until at least day 28. A comparison of the areas under the curve (concentration versus time) showed a >3-fold potency with vitamin D<sub>3</sub>. Clearly, vitamin D<sub>2</sub> would show efficacy in the treatment of severe vitamin D deficiency; however, the authors note that 2000 μg (50 000 IU) vitamin D<sub>2</sub> should be considered equivalent to ≤375 μg (15000 IU) vitamin D<sub>3</sub>, and likely closer to 125 μg (5000 IU) vitamin D<sub>3</sub> (21).

Several mechanisms could contribute to the greater capacity of vitamin D<sub>3</sub> to maintain higher 25(OH)D concentrations over time. Supplementation of vitamin D<sub>2</sub> produces appreciable amounts of serum 25(OH)D<sub>2</sub> (22), which, as previously mentioned, has a lower affinity for DBP and results in a shorter circulating half-life than that of 25(OH)D<sub>3</sub>. Others have suggested a higher affinity of hepatic 25-hydroxylase for vitamin D<sub>3</sub> than for vitamin D<sub>2</sub> (23). In the liver, hepatic enzyme 25-hydroxylase places a hydroxyl group in the 25 position of the molecule, resulting in the formation of 25(OH)D. This reaction is the initial step in the activation of vitamin D before its metabolism in the kidney to its hormonally active form, 1,25(OH)<sub>2</sub>D. In rats, vitamin D 25-hydroxylase has been shown to exist in liver mitochondrial and microsomal fractions. In humans, previous work has shown that mitochondrial vitamin D 25-hydroxylase presides and converts vitamin D<sub>3</sub> to 25(OH)D<sub>3</sub> 5 times as fast as it does vitamin D<sub>2</sub> to form 25(OH)D<sub>2</sub> (23). The human microsomal fraction also was shown to hydroxylate vitamin D<sub>3</sub> to some degree, but no detectable vitamin D 25-hydroxylation of vitamin D<sub>2</sub> was observed (23). However, studies have identified a key microsomal liver enzyme (cytochrome P450, CYP2R1) in humans that appears able to 25-hydroxylate both vitamin D<sub>2</sub> and D<sub>3</sub>, whereas the mitochondrial enzyme (CYP27A1) only 25-hydroxylates vitamin D<sub>3</sub> (24, 25).

#### DIFFERENT METABOLIC FATES OF VITAMINS D<sub>2</sub> AND D<sub>3</sub>

It was initially thought that both vitamin D<sub>2</sub> and vitamin D<sub>3</sub> follow the same metabolic pathway. However, minor differences in the chemistry of side chains between the 2 forms of vitamin D result in differences in the site of hydroxylation and leads to the production of unique biologically active metabolites (26).

After 25-hydroxylation, 25(OH)D and 1,25(OH)<sub>2</sub>D undergo additional 24-hydroxylation in the kidney to form 24,25(OH)<sub>2</sub>D and 1,24,25(OH)<sub>3</sub>D, respectively. The formation of 1,24,25(OH)<sub>3</sub>D<sub>2</sub> leads to deactivation of the vitamin D<sub>2</sub> molecule, whereas the analogous vitamin D<sub>3</sub> metabolite, 1,24,25(OH)<sub>3</sub>D<sub>3</sub>, must undergo additional side-chain oxidation to be biologically deactivated (27). In fact, 1,24,25(OH)<sub>3</sub>D<sub>3</sub> has the ability to bind to the vitamin D receptor [VDR; ≈40% more than 1,25(OH)<sub>2</sub>D<sub>3</sub>] and, thus, is able to potentially generate significant biological activity. It was suggested that this 24-hydroxylation of the side chain could occur only after 25-hydroxylation (15). Although this may be the case for vitamin D<sub>3</sub>, it does not appear to be a prerequisite for vitamin D<sub>2</sub>; evidence (28–30) suggests that 24-hydroxylation of the vitamin D<sub>2</sub> side chain can also occur in the liver, resulting in a significant (20–50%) formation of 24(OH)D<sub>2</sub> (29). Consequently, 1,24(OH)<sub>2</sub>D<sub>2</sub>, formed in the kidney from 24(OH)D<sub>2</sub>, has less affinity for VDR than do 1,25(OH)<sub>2</sub>D<sub>3</sub> and 1,24(OH)<sub>2</sub>D<sub>3</sub> (31). Binding to VDR represents a molecular event important to the biological action of the vitamin D metabolites. Taken together, the most plausible explanations for the greater bioefficacy of vitamin D<sub>3</sub> are conceivably due to the higher affinities of vitamin D<sub>3</sub> and its metabolites than vitamin D<sub>2</sub> for hepatic 25-hydroxylase, DBP, and VDR and because vitamin D<sub>3</sub> is not directly metabolized to 24(OH)D as is vitamin D<sub>2</sub>.

#### FORM OF VITAMIN D USED IN CLINICAL STUDIES

As with all drugs that differ in molecular structure, care should be taken to distinguish the form of vitamin D used in clinical studies. For example, after vitamin D<sub>2</sub> supplementation, Harris et al (32) reported almost double the increase in 25(OH)D concentrations in young men compared with those in older men. This result suggested a general age-related impairment in vitamin D metabolism. However, a follow-up study by the same researchers in which they used supplemental vitamin D<sub>3</sub> instead of vitamin D<sub>2</sub> showed similar increases in plasma concentrations of 25(OH)D between age groups (33). Harris et al (33) then reaffirmed that although there are age-related changes in vitamin D metabolism, impairment with age pertains solely to vitamin D<sub>2</sub> metabolism.

An older clinical trial in which vitamin D<sub>2</sub> was used showed prevention loss of bone density on the basis of radiographs of the hand (34), whereas another trial showed no effect on the basis of dual-energy X-ray absorptiometry (35). One clinical trial showed that, similar to supplementation with vitamin D<sub>3</sub> (36), supplementation with vitamin D<sub>2</sub> caused a reduction in the rate of falls (37); however, another trial using vitamin D<sub>2</sub> showed no effect (38). Studies using vitamin D<sub>3</sub> have consistently shown preservation of bone density in older adults who adhered to a protocol of daily doses of >10 μg (400 IU) (39, 40). In fact, all successful fracture trials have used vitamin D<sub>3</sub> at doses of ≈20 μg (800 IU)/d (41).

#### Stability of vitamin D<sub>2</sub> preparations

Synthetic production of vitamin D<sub>3</sub> is manufactured in a similar manner to that which occurs naturally in human and animal skin, via the production of 7-dehydrocholesterol from cholesterol and subsequent irradiation to its active D<sub>3</sub> form. Conversely, vitamin D<sub>2</sub> is synthetically produced from irradiation of ergosterol derived from the mold ergot (42). In addition to its lower bioactivity, the poor stability of vitamin D<sub>2</sub> is worrisome, particularly upon exposure of crystalline D<sub>2</sub> powder to varying

temperatures, humidity, or even storage containers (43, 44). In contrast, vitamin D<sub>3</sub> powder is not as labile. As a result, the vitamin D content by various manufacturers has been found to differ substantially from that of the labeled claim (17). It must be noted that comparative published data on the stability of vitamin D<sub>3</sub> and D<sub>2</sub> in oil is lacking. The poorer stability of and greater impurities in vitamin D<sub>2</sub> powders may also lead to a higher risk of toxicity than that associated with the vitamin D<sub>3</sub> metabolites. However, it is more likely that the weaker affinity of vitamin D<sub>2</sub> metabolites to DBP produces higher and more biologically available proportions of free 25(OH)D<sub>2</sub> and 1,25-(OH)<sub>2</sub>D<sub>2</sub> and may thus be responsible for the greater risk of D<sub>2</sub> toxicity (45).

#### Assessment of vitamin D status after D<sub>2</sub> supplementation: challenges to assay methodology

The production of 25(OH)D<sub>2</sub> as a result of vitamin D<sub>2</sub> supplementation may additionally hinder the assessment of total circulating 25(OH)D, because common assay systems used for clinical purposes have either a diminished capacity or do not detect 25(OH)D<sub>2</sub> with the same efficiency as 25(OH)D<sub>3</sub> (46). Thus, clinical assays used to monitor vitamin D<sub>2</sub> treatment may lead to an erroneous underestimation of vitamin D status. This occurrence may result in additional supplementation with potential adverse consequences, such as hypervitaminosis D.

#### CONCLUSION

Vitamin D<sub>2</sub>, if given in high enough doses, prevents infantile rickets and is capable of healing adult osteomalacia. However, the inefficiency of vitamin D<sub>2</sub> compared with vitamin D<sub>3</sub>, on a per mole basis, at increasing 25(OH)D is now well documented, and no successful clinical trials to date have shown that vitamin D<sub>2</sub> prevents fractures (19–21, 47). Given the assumption that the intake of any nutrient will deliver defined effects [ie, supplementation with vitamin D will lead to an increase in 25(OH)D or fracture prevention], it is clear that vitamin D<sub>2</sub> does not fit this current nutritional notion. This is not to suggest that vitamin D<sub>2</sub> is not efficacious, but, because the units of the 2 forms is clearly not equivalent, likely due to its distinct metabolic features and diminished binding of vitamin D<sub>2</sub> metabolites to DBP in plasma, continual application of vitamin D<sub>2</sub> in clinical use, including in research trials, only serves to confound our understanding of optimal vitamin D dosing recommendations. Furthermore, the public expects to derive the equivalent effect per unit dose of vitamin D, whether it is vitamin D<sub>2</sub> or vitamin D<sub>3</sub>. The scientific community is aware that these molecules are not equivalent. Therefore, vitamin D<sub>2</sub> should no longer be regarded as a nutrient appropriate for supplementation or fortification of foods. ☞

The manuscript was written by LAH and RV. Neither of the authors had any personal or financial conflicts of interest in the writing of this article.

#### REFERENCES

1. Committee of Revision. Drug information for the health care professional. Rockville, MD: United States Pharmacopeial Convention, Inc, 1997.
2. Institute of Medicine. Standing Committee on the Scientific Evaluation of Dietary Reference Intakes. Vitamin D. Dietary reference intakes: calcium, phosphorus, magnesium, vitamin D, and fluoride. Washington, DC: National Academy Press, 1997:250–87.
3. Medicines Commission. British Pharmacopoeia 1980. London, United Kingdom: Her Majesty's Stationery Office, 1980.
4. WARF Wisconsin Alumni Research Foundation. Steenbock and



- WARF's founding. Internet: <http://www.warf.org/about/> (accessed 06 January 2006).
- Hess AF, Lewis JM, Rivkin H. Newer aspects of the therapeutics of viosterol (irradiated ergosterol). *JAMA* 1930;94:1885.
  - Park EA. The therapy of rickets. *JAMA* 1940;115:370–9.
  - World Health Organization. Expert committee on biological standardization, report of the subcommittee on fat soluble vitamins. *World Health Organ Tech Rep Ser* 1950;3:7.
  - Klinke K, Bogner W, Gleiss J. Zur dosierung des Vigantol D3 bei Fruehgeborenen. [The dosing of premies with Vigantol/vitamin D<sub>3</sub>.] *Deutsche Med Wochenschrift* 1954;79:370–1.
  - Norman AW. Problems relating to the definition of an international unit for Vitamin D and its metabolites. *J Nutr* 1972;102:1243–6.
  - Specker BL, Ho ML, Oestreich A, et al. Prospective study of vitamin D supplementation and rickets in China. *J Pediatr* 1992;120:733–9.
  - Hoy DA, Ramberg CF, Horst RL. Evidence that discrimination against ergocalciferol by the chick is the result of enhanced metabolic clearance rates for its mono- and dihydroxylated metabolites. *J Nutr* 1988;118:633–8.
  - Marx SJ, Jones G, Weinstein RS, Chrousos GP, Renquist DM. Differences in mineral metabolism among nonhuman primates receiving diets with only vitamin D<sub>3</sub> or only vitamin D<sub>2</sub>. *J Clin Endocrinol Metab* 1989;69:1282–9.
  - Horst RL, Napoli JL, Littledike ET. Discrimination in the metabolism of orally dosed ergocalciferol and cholecalciferol by the pig, rat and chick. *Biochem J* 1982;204:185–9.
  - Hollis BW. Comparison of equilibrium and disequilibrium assay conditions for ergocalciferol, cholecalciferol and their metabolites. *J Steroid Biochem* 1984;21:81–6.
  - Jones G. Analog metabolism. In: Feldman D, Glorieux F, Pike JW, eds. *Vitamin D*. New York, NY: Elsevier Academic Press, 1997:973–94.
  - Hartwell D, Hassager C, Christiansen C. Effect of Vitamin D<sub>2</sub> and Vitamin D<sub>3</sub> on the serum concentrations of 1,25(OH)<sub>2</sub>D<sub>2</sub> and 1,25(OH)<sub>2</sub>D<sub>3</sub> in normal subjects. *Acta Endocrinol (Copenh)* 1987;115:378–84.
  - Whyte MP, Haddad JG Jr, Walters DD, Stamp TCB. Vitamin D bioavailability: serum 25-Hydroxyvitamin D levels in man after oral, subcutaneous, intramuscular, and intravenous vitamin D administration. *J Clin Endocrinol Metab* 1979;48:906–11.
  - Tjellesen L, Hummer L, Christiansen C, Rodbro P. Serum concentration of vitamin D metabolites during treatment with vitamin D<sub>2</sub> and D<sub>3</sub> in normal premenopausal women. *Bone Miner* 1986;1:407–13.
  - Trang H, Cole DE, Rubin LA, Pierratos A, Siu S, Vieth R. Evidence that vitamin D<sub>3</sub> increases serum 25-hydroxyvitamin D more efficiently than does vitamin D<sub>2</sub>. *Am J Clin Nutr* 1998;68:854–48.
  - Mastaglia SR, Mautalen CA, Parisi MS, Oliveri B. Vitamin D<sub>2</sub> dose required to rapidly increase 25OHD levels in osteoporotic women. *Eur J Clin Nutr* 2006;60:681–7.
  - Armas LA, Hollis BW, Heaney RP. Vitamin D<sub>2</sub> is much less effective than vitamin D<sub>3</sub> in humans. *J Clin Endocrinol Metab* 2004;89:5387–91.
  - Rapuri PB, Gallagher JC, Haynatzki G. Effect of vitamins D<sub>2</sub> and D<sub>3</sub> supplement use on serum 25OHD concentration in elderly women in summer and winter. *Calcified Tissue International* 2004;74:150–6.
  - Holmberg I, Berlin T, Ewerth S, Bjorkhem I. 25-Hydroxylase activity in subcellular fractions from human liver. Evidence for different rates of mitochondrial hydroxylation of vitamin D<sub>2</sub> and D<sub>3</sub>. *Scand J Clin Lab Invest* 1986;46:785–90.
  - Cheng JB, Motola DL, Mangelsdorf DJ, Russell DW. De-ophanization of cytochrome P450 2R1. A microsomal vitamin D 25-hydroxylase. *J Biol Chem* 2003;278:38084–93.
  - Cheng JB, Levine MA, Bell NH, Mangelsdorf DJ, Russell DW. Genetic evidence that the human CYP2R1 enzyme is a key vitamin D 25-hydroxylase. *Proc Natl Acad Sci U S A* 2004;101:7711–5.
  - Horst RL, Reinhardt TA, Reddy S. Vitamin D metabolism. In: Feldman D, Pike JW, Glorieux FH, eds. *Vitamin D*. London, United Kingdom: Elsevier Academic Press, 2005:15–36.
  - Horst RL, Reinhardt TA, Ramberg CF, Koszewski NJ, Napoli JL. 24-Hydroxylation of 1,25-dihydroxyergocalciferol: an unambiguous deactivation process. *J Biol Chem* 1986;261:9250–6.
  - Jones G, Schnoes HK, Kevan L, De Luca HF. Isolation and identification of 24-hydroxyvitamin D<sub>2</sub> represents a minor physiological pathway for the activation of vitamin D<sub>2</sub> in mammals. *Arch Biochem Biophys* 1980;202:450–7.
  - Horst RL, Koszewski NJ, Reinhardt TA. 1 alpha-hydroxylation of 24-hydroxyvitamin D<sub>2</sub> represents a minor physiological pathway for the activation of vitamin D<sub>2</sub> in mammals. *Biochemistry* 1990;29:578–82.
  - Mawer EB, Jones G, Davies M, et al. Unique 24-hydroxylated metabolites represent a significant pathway of metabolism of vitamin D<sub>2</sub> in humans: 24-hydroxyvitamin D<sub>2</sub> and 1,24-dihydroxyvitamin D<sub>2</sub> detectable in human serum. *J Clin Endocrinol Metab* 1998;83:2156–66.
  - Horst RL, Prapong S, Reinhardt TA, Koszewski NJ, Knutson J, Bishop C. Comparison of the relative effects of 1,24-dihydroxyvitamin D<sub>2</sub> [1,24-(OH)<sub>2</sub>D<sub>2</sub>], 1,24-dihydroxyvitamin D<sub>3</sub> [1,24-(OH)<sub>2</sub>D<sub>3</sub>], and 1,25-dihydroxyvitamin D<sub>3</sub> [1,25-(OH)<sub>2</sub>D<sub>3</sub>] on selected vitamin D-regulated events in the rat. *Biochem Pharmacol* 2000;60:701–8.
  - Harris SS, Dawson-Hughes B, Perrone GA. Plasma 25-hydroxyvitamin D responses of younger and older men to three weeks of supplementation with 1800 IU/day of vitamin D. *J Am Coll Nutr* 1999;18:470–4.
  - Harris SS, Dawson-Hughes B. Plasma vitamin D and 25OHD responses of young and old men to supplementation with vitamin D<sub>3</sub>. *J Am Coll Nutr* 2002;21:357–62.
  - Nordin BE, Baker MR, Horsman A, Peacock M. A prospective trial of the effect of vitamin D supplementation on metacarpal bone loss in elderly women. *Am J Clin Nutr* 1985;42:470–4.
  - Cooper L, Clifton-Bligh PB, Nery ML, et al. Vitamin D supplementation and bone mineral density in early postmenopausal women. *Am J Clin Nutr* 2003;77:1324–9.
  - Bischoff HA, Stahelin HB, Dick W et al. Effects of vitamin D and calcium supplementation on falls: a randomized controlled trial. *J Bone Miner Res* 2003;18:343–51.
  - Flicker L, MacInnis RJ, Stein MS, et al. Should older people in residential care receive vitamin D to prevent falls? Results of a randomized trial. *J Am Geriatr Soc* 2005;53:1881–8.
  - Law M, Withers H, Morris J, Anderson F. Vitamin D supplementation and the prevention of fractures and falls: results of a randomised trial in elderly people in residential accommodation. *Age Ageing* 2006;35:482–6.
  - Chapuy MC, Arlot ME, Duboeuf F, et al. Vitamin D<sub>3</sub> and calcium to prevent hip fractures in the elderly women. *N Engl J Med* 1992;327:1637–42.
  - Ooms ME, Roos JC, Bezemer PD, van der Vijgh WJ, Bouter LM, Lips P. Prevention of bone loss by vitamin D supplementation in elderly women: a randomized double-blind trial. *J Clin Endocrinol Metab* 1995;80:1052–8.
  - Bischoff-Ferrari HA, Willett WC, Wong JB, Giovannucci E, Dietrich T, Wason-Hughes B. Fracture prevention with vitamin D supplementation: a meta-analysis of randomized controlled trials. *JAMA* 2005;293:2257–64.
  - De Luca HF. Overview of general physiologic features and functions of vitamin D. *Am J Clin Nutr* 2004;80(suppl):1689S–96S.
  - Grady LT, Thakker KD. Stability of solid drugs: degradation of ergocalciferol (vitamin D<sub>2</sub>) and cholecalciferol (vitamin D<sub>3</sub>) at high humidity and elevated temperatures. *J Pharm Sci* 1980;69:1099–102.
  - Huber W, Barlow OW. Chemical and biological stability of crystalline vitamins D<sub>2</sub> and D<sub>3</sub> and their derivatives. *J Biol Chem* 1943;149:125–37.
  - Vieth R, Chan PC, MacFarlane GD. Efficacy and safety of vitamin D<sub>3</sub> intake exceeding the lowest observed adverse effect level. *Am J Clin Nutr* 2001;73:288–94.
  - Hollis BW. The determination of circulating 25-hydroxyvitamin D: no easy task. *J Clin Endocrinol Metab* 2004;89:3149–51.
  - Tjellesen L, Christiansen C, Hummer L. A comparison of vitamin D<sub>2</sub> and D<sub>3</sub> in man. In: Norman AW, Schaefer K, Grigoleit H-G, Vaamonde J, eds. *Vitamin D, chemical, biochemical and clinical update*. Berlin, Germany: Walter deGruyter, 1985;3–12.

