Available online at www.sciencedirect.com
SCIENCE DIRECT®
Progress in Biophysics and Molecular Biology 92 (2006) 49–59
Progress in Biophysics & Molecular Biology
www.elsevier.com/locate/pbiomolbio

Review

Vitamin D: Its role in cancer prevention and treatment

Michael F. Holick*

Boston University Medical Center, 715 Albany Street, M-1013, Boston, MA 02118, USA

Available online 10 March 2006

Abstract

Vitamin D, the sunshine vitamin, has been recognized for almost 100 years as being essential for bone health. Vitamin D provides an adequate amount of calcium and phosphorus for the normal development and mineralization of a healthy skeleton. Vitamin D made in the skin or ingested in the diet, however, is biologically inactive and requires obligate hydroxylations first in the liver to 25-hydroxyvitamin D, and then in the kidney to 1,25-dihydroxyvitamin D. 25-Hydroxyvitamin D is the major circulating form of vitamin D that is the best indicator of vitamin D status. 1,25-dihydroxyvitamin D is the biologically active form of vitamin D. This lipid-soluble hormone interacts with its specific nuclear receptor in the intestine and bone to regulate calcium metabolism. It is now recognized that the vitamin D receptor is also present in most tissues and cells in the body. 1,25-dihydroxyvitamin D, by interacting with its receptor in non-calcemic tissues, is able to elicit a wide variety of biologic responses. 1,25-dihydroxyvitamin D regulates cellular growth and influences the modulation of the immune system. There is compelling epidemiologic observations that suggest that living at higher latitudes is associated with increased risk of many common deadly cancers. Both prospective and retrospective studies help support the concept that it is vitamin D deficiency that is the driving force for increased risk of common cancers in people living at higher latitudes. Most tissues and cells not only have a vitamin D receptor, but also have the ability to make 1,25-dihydroxyvitamin D. It has been suggested that increasing vitamin D intake or sun exposure increases circulating concentrations of 25-hydroxyvitamin D, which in turn, is metabolized to 1,25-dihydroxyvitamin D_3 in prostate, colon, breast, etc. The local cellular production of 1,25-dihydroxyvitamin D acts in an autocrine fashion to regulate cell growth and decrease the risk of the cells becoming malignant. Therefore, measurement of 25-hydroxyvitamin D is important not only to monitor vitamin D status for bone health, but also for cancer prevention.

Keywords: Vitamin D; Cancer; Sunlight; Ultraviolet radiation; Bone health

Contents

1. Sources and metabolism of vitamin D 50
2. Role of $1,25(OH)_2D$ in regulating cell growth. 50
3. The sunlight-vitamin D cancer conundrum. 52
4. Sunlight, vitamin D and cancer prevention. 53
5. Vitamin D fortification and the vitamin D intoxication scare. 53
6. The development of vitamin D analogs for cancer treatment 55

*Corresponding author. Tel.: +1 617 638 4545; fax: +1 617 638 8882.
E-mail address: mfholick@bu.edu.

0079-6107/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pbiomolbio.2006.02.014

7. Recommendations 55
8. Conclusion 56
Acknowledgements 57
References 57

1. Sources and metabolism of vitamin D

Very few foods naturally contain vitamin D (Vieth, 2005; Holick, 2004a, b; Holick, 2002a, b). This is the reason why at the turn of the 20th century, more than 80% of children living in the industrialized cities of Northern Europe and Northeastern United States were crippled by the bone deforming disease, rickets. Typically, oily fish including salmon, mackerel and herring; cod-liver oil and sun-dried mushrooms, contain approximately 300–500 IU of either vitamin D_3 or vitamin D_2 per serving (Vieth, 2005; Holick, 2004a, b; Holick, 2002a, b) (D represents D_2 and or D_3). The major foods in the United States that are fortified with vitamin D include milk, orange juice, and some cereals, bread, yogurt and cheeses. In Europe the fortification of various foods including dairy products, custards was routinely practiced until the late 1940s when an outbreak of vitamin D intoxication resulted in laws being passed to forbid the fortification of milk and a wide variety of other products with vitamin D. Most European countries permit margarine and some cereals to be fortified with vitamin D, and a few countries including Sweden also permit milk to be fortified with this vitamin.

The action of sunlight on the skin resulting in the production of vitamin D_3 is responsible for most (90–95%) of peoples' vitamin D requirement (Holick, 2004a, b; Holick, 2002a, b). During exposure to sunlight it is the ultraviolet B portion (with energies between 290 and 315 nm) that is absorbed by 7-dehydrocholesterol in the epidermis and dermis that results in its conversion to previtamin D_3 (Fig. 1). Previtamin D_3 is rapidly isomerized by the body temperature to vitamin D_3. Once formed, vitamin D_3 is ejected out of the plasma membrane into the extracellular space where it enters the dermal capillary bed bound to the vitamin-D-binding protein.

Vitamin D_3 from the skin and vitamin D_2 and vitamin D_3 from the diet are metabolized in the liver to 25-hydroxyvitamin D [25(OH)D]. 25(OH)D is the major circulating form of vitamin D that is used by clinicians to determine the vitamin D status of their patients. However, 25(OH)D is biologically inert and requires an additional hydroxylation in the kidney to form the biologically active form of vitamin D; 1,25-dihydroxyvitamin D [1,25$(OH)_2$D] (Fig. 1) (DeLuca, 2004; Holick, 2004a, b; Holick, 2002a, b).

1,25$(OH)_2$D is a lipid-soluble hormone that interacts with its vitamin D receptor (VDR) in the small intestine to increase the expression of an epithelial calcium channel, calcium-binding protein and a variety of other proteins to help the transport of calcium from the intestinal lumen into the circulation. 1,25$(OH)_2$D also interacts with its VDR in the osteoblasts, which stimulates the expression of the receptor activator of NFκB ligand (RANKL). This results in a cascading effect to increase the mobilization of osteoclast precursors to become mature osteoclasts, which in turn, mobilize calcium stores from the skeleton to maintain calcium homeostasis (DeLuca, 2004; Holick, 2004a, b; Holick, 2002a, b; Khosla, 2001; Norman et al., 2002).

2. Role of 1,25$(OH)_2$D in regulating cell growth

In 1979, Stumpf et al. (1979) reported that not only the intestine, bone and kidney had a VDR, but also that it appeared that essentially all tissues in the body recognized 1,25$(OH)_2$D. Shortly thereafter, a variety of studies revealed that the skin, colon, prostate, breast, heart, skeletal muscle, brain, monocytes and activated T and B lymphocytes all expressed VDR. The first insight into the potential non-calcemic role of 1,25$(OH)_2$D on cellular activity was reported by Suda et al. (1982) when they observed that the growth of M-1 leukemic cells that had a VDR was markedly inhibited by 1,25$(OH)_2D_3$. In addition, they observed that 1,25$(OH)_2D_3$ induced M-1 cell differentiation. This was quickly followed by the observation that human HL-60 leukemic cells that had a VDR responded in a similar manner (Tanaka et al., 1982). Since these insightful observations, it has been observed that cultured breast, colon, prostate, skin, lung and a variety of other cell lines, when

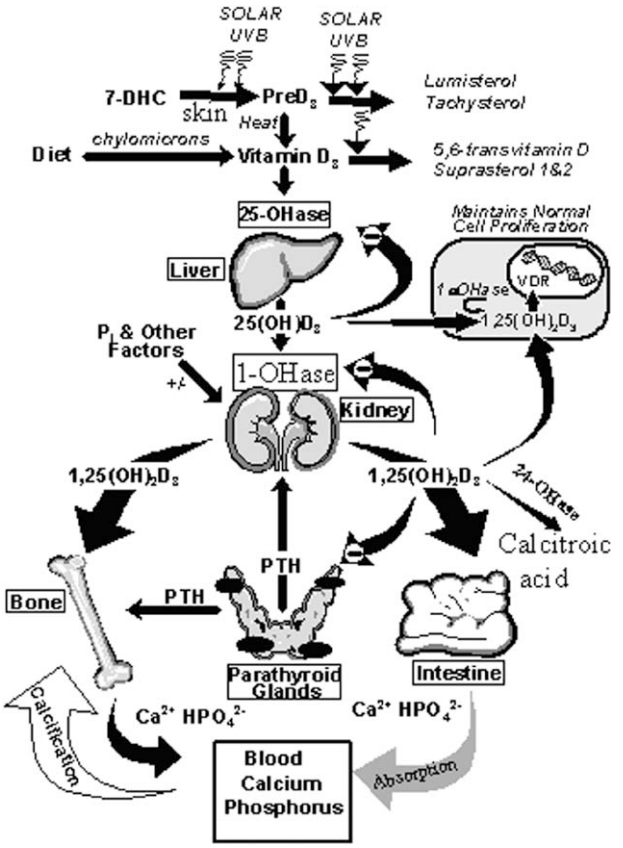

Fig. 1. Schematic representation for cutaneous production of vitamin D and its metabolism and regulation for calcium homeostasis and cellular growth. During exposure to sunlight, 7-dehydrocholesterol (7-DHC) in the skin absorbs solar ultraviolet (UVB) radiation and is converted to previtamin D_3 (preD_3). Once formed, D_3 undergoes thermally induced transformation to vitamin D_3. Further exposure to sunlight converts preD_3 and vitamin D_3 to biologically inert photoproducts. Vitamin D coming form the diet or from the skin enters the circulation and is metabolized in the liver by the vitamin D-25-hydroxylase (25-OHase) to 25-hydroxyvitamin D_3 [25(OH)D_3] 25(OH)D_3 re-enters the circulation and is converted in the kidney by the 25-hydroxyvitamin D_3-1α-hydroxylase (1-OHase) to 1,25-dihydroxyvitamin D_3 [1,25$(OH)_2D_3$]. A variety of factors, including serum phosphorus (P_i) and parathyroid hormone (PTH) regulated the renal production of 1,25$(OH)_2$D. 1,25$(OH)_2$D regulates calcium metabolism through its interaction with its major target tissues, the bone and the intestine. 1,25$(OH)_2D_3$ also induces its own destruction by enhancing the expression of the 25-hydroxyvitamin D-24-hydroxylase (24-OHase). 25(OH)D is metabolized in other tissues for the purpose of regulation of cellular growth. (Copyright Michael F. Holick, 2003, used with permission).

exposed to 1,25$(OH)_2D_3$, had marked inhibition of cellular growth and induction of terminal differentiation (DeLuca, 2004; Feldman et al., 2000; Holick, 2004a, b; Holick, 2002a, b; Norman et al., 2002).

In addition, cancer cell lines of the prostate, colon, breast, lung and melanoma that had a VDR had marked inhibition of cellular growth when exposed to 1,25$(OH)_2$D (Colston et al., 1981a, b; Feldman et al., 2000; Holick, 2004a, b; Holick, 2002a, b; Skowronski et al., 1993) (Fig. 2).

There was great excitement about the possibility of developing 1,25$(OH)_2$D and its analogs for the treatment of cancer. Koeffler et al. (1985) initiated one of the first studies and reported significant remission in patients suffering from preleukemia who were treated with 1,25$(OH)_2D_3$. Unfortunately, the patients not only developed hypercalcemia, but also became unresponsive to the antiproliferative and prodifferentiating effects of 1,25$(OH)_2D_3$, and ultimately succumbed to their illness. This put a significant damper on the development of vitamin D analogs for the treatment of cancer. However, it was also appreciated that epidermal cells when, exposed to 1,25$(OH)_2D_3$ in culture, had marked inhibition of their growth and they terminally differentiated. Thus, it was reasoned that 1,25$(OH)_2D_3$ and it analogs could be developed as effective treatment for the hyperproliferative epidermal disorder, psoriasis (MacLaughlin et al., 1985). 1,25$(OH)_2D_3$, calcipotriene,

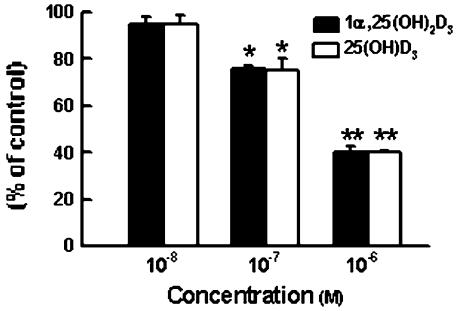

Fig. 2. Effect of $1\alpha,25(OH)_2D_3$ and $25(OH)D_3$ on cell proliferation in prostate primary cultures. Results are presented as the means ± SD of 9 determinations. $^{*}P<0.05$, $^{**}P<0.001$ vs. controls. No statistical difference between $1\alpha,25(OH)_2D_3$ and $25(OH)_2D_3$ was observed among the dosages studied. (Reproduced with permission from Chen et al., Clin Cancer Res 6: 901–908, 2000).

1,24-dihydroxyvitamin D_3 and 22-oxo-1,25-dihydroxyvitamin D_3 have been developed as effective antipsoriatic agents. Thus, the antiproliferative effectiveness of $1,25(OH)_2D_3$ and its analogs for the treatment of hyperproliferative disorders was established (Holick, 1998).

3. The sunlight-vitamin D cancer conundrum

In 1941 Apperly (1941) made a curious observation, i.e. people living in northern latitudes in the United States including Vermont, New Hampshire and Massachusetts were more likely to die of cancer than adults living in Alabama, South Carolina and Texas as well as other southern states. He did note, however, that people living in southern states were more likely to develop non-life threatening skin cancer, and suggested that this provided an immunity for the more serious deadly cancers of the breast, colon and prostate. This insightful observation went unnoticed until the late 1980s when Garland et al. (1991, 1989) reported that colon cancer mortality was much higher in Northeastern United States compared to people living in southern states. It is now well documented that the risk of developing and dying of prostate, breast, colon, ovarian, esophageal, non-Hodgkin's lymphoma and a variety of other lethal cancers is related to living at higher latitudes (Bertone-Johnson et al., 2005; Freedman et al., 2002; Garland et al., 1991, 1990, 1989, 1985; Grant, 2004, 2002a, 2002b; Janowsky et al., 1999; John et al., 1999; Lefkowitz and Garland, 1994; Tangrea et al., 1997; Zhao and Feldman, 2001).

The simple explanation for why exposure to sunlight decreased risk of common cancers was that by increasing the production of vitamin D_3 in the skin resulted in higher circulating levels of $25(OH)D_3$, which could be metabolized by the kidney to $1,25(OH)_2D_3$. Thus, by increasing circulating levels of $1,25(OH)_2D_3$, it could interact with the other tissues in the body that had a VDR, which helped maintain cellular growth and to prevent the cells from becoming malignant. Although the exact mechanism for how $1,25(OH)_2D$ accomplishes this is not well understood, it has been reported that $1,25(OH)_2D$ markedly inhibited a variety of genes responsible for proliferation including p21 and p27, and was also responsible for enhancing apoptosis genes, and a variety of genes that regulate cellular differentiation (Chen and Holick, 2003; Feldman et al., 2000; Holick, 2004a, b; Holick, 2002a, b). This all seemed to make sense except for the fact that the kidney's production of $1,25(OH)_2D_3$ is exquisitely regulated by parathyroid hormone, serum calcium and phosphorus and several other hormones (Holick, 2004a, b; Holick, 2002a, b). Thus, increasing vitamin D intake or increasing sun exposure does not result in increased circulating levels of $1,25(OH)_2D_3$.

In the 1980s cultured keratinocytes and a variety of other cultured cells were reported to have the enzymatic machinery to produce $1,25(OH)_2D$ (Bikle et al., 1986). However, the importance of these observations was not fully appreciated until Schwartz et al. (1998) reported that prostate cells obtain from prostate biopsies converted $25(OH)D_3$ to $1,25(OH)_2D_3$. Since this observation, it has been observed that the colon, lung, breast among other tissues all express the 25-hydroxyvitamin D-1α-hydroxylase (1-OHase; cyp 27 B1) (Cross et al., 2001; Mawer et al., 1994; Tangpricha et al., 2001). Thus, it has been suggested that raising blood levels of 25(OH)D provides an adequate substrate for the prostate, colon and breast to make their own $1,25(OH)_2D$, which, in turn, is capable of regulating a variety of cellular processes that helps to keep in check cellular

growth and prevent malignancy (Fig. 2). Once $1,25(OH)_2D$ carries out this important function, it induces its own destruction by regulating the 25-hydroxyvitamin D-24-hydroxalase (cyp 24) (Omdahl et al., 2002). This enzyme hydroxylates $1,25(OH)_2D$ on carbon-24 that initiates a cascade of oxidative events resulting in the production of the water-soluble and biologically inactive calcitroic acid, which is excreted by the kidney into the urine (Fig. 1).

4. Sunlight, vitamin D and cancer prevention

The observations by Garland et al. (1991, 1989, 1985), Hanchette and Schwartz (1992), and Grant et al. (2002a,b, 2004), set the stage for linking living at higher latitudes and being vitamin D deficient with increased risk of common deadly cancers. It was reported that in both prospective and retrospective studies that if 25(OH)D was at least 50 nmol/L (20 ng/mL) that there was a decreased risk of developing prostate, breast and colon cancer by 30–50% (Garland et al., 1989; Ahonen et al., 2000). It was suggested by Grant that 25% of breast cancer mortality in Europe was due to living at higher latitude and being vitamin D deficient (Grant, 2002a).

The initial observation by Apperly (1941) has been confirmed by several investigators, most recently Grant who reported that increased sun exposure decreases mortality due to common cancers in both white males and females (Grant, 2002b; Grant and Holick, 2005). These observations are also supported by Luscombe et al. (2001) who reported that men who had little sun exposure developed prostate cancer 3–5 years early than men who had the most sun exposure.

We also evaluated colon cancer incidence in California because the state has wide range of latitudes. We observed that living in San Diego significantly decreased the risk of developing colon cancer compared to Californians living in San Francisco and further north (Spina et al., 2005).

However, it remained to be determined whether vitamin D deficiency per se increased tumor growth. To evaluate this, Tangpricha et al. (2005) conducted a study whereby they evaluated the growth of a mouse colon cancer cell line MC-26 in Balb/c mice that were vitamin D deficient or vitamin D sufficient. The cells were implanted in the backs of both groups of animals and by day 9, the tumors became apparent. By day 10, there was a statistically significant difference in the tumor size in the mice that were vitamin D deficient compared to the group that were vitamin D sufficient. The tumors grew much more rapidly in the vitamin D deficient mice, and by the end of the study on day 19, the tumors in the mice that were vitamin D deficient were on average 80% larger than in the mice that were vitamin D sufficient. The 25(OH)D levels in the vitamin D deficient mice at the end of the study was <5 ng/mL, whereas the vitamin D sufficient mice maintained a 25(OH)D of 35 ng/mL. This observation provides strong corroborating data that supports the concept that vitamin D sufficiency is important for reducing tumor cell growth.

Whitlatch et al. (2002) conducted a study that provided strong evidence that the local production of $1,25(OH)_2D_3$ in prostate cells is important for regulating prostate cancer cell growth and differentiation. They grew a prostate cancer cell line LNCaP, which has a VDR but has no 1-OHase activity. These cells had marked inhibition of cellular growth when incubated with $1,25(OH)_2D_3$. These cells are unresponsive to $25(OH)D_3$. The LNCaP cells were transfected with the 1-OHase gene or its antisense counterpart. The cells transfected with the 1-OHase gene were able to metabolize ^{3}H-$25(OH)D_3$ to ^{3}H-$1,25(OH)_2D_3$. When the 1-OHase transfected LNCaP cells were treated with $25(OH)D_3$, there was marked inhibition of cell growth. The normal LNCaP cells and the LNCaP cells transfected with either an empty vector or the antisense gene showed no antiproliferative activity in response to $25(OH)D_3$ (Fig. 3). These data strongly support the theory that by raising blood levels of $25(OH)D_3$ that this provides adequate substrate for the 1-OHase that is present in the breast, colon, prostate and other tissues once it is metabolized to $1,25(OH)_2D_3$ it modulates cellular growth and prevents malignancy (Fig. 4).

5. Vitamin D fortification and the vitamin D intoxication scare

In the late 1920s and early 1930s when it was appreciated that exposure to sunlight or artificial ultraviolet B radiation (UV) imparted antirachitic activity, this led to the ultraviolet irradiation of a wide variety of foods to impart antirachitic activity and help prevent rickets in children. Once vitamin D was discovered and

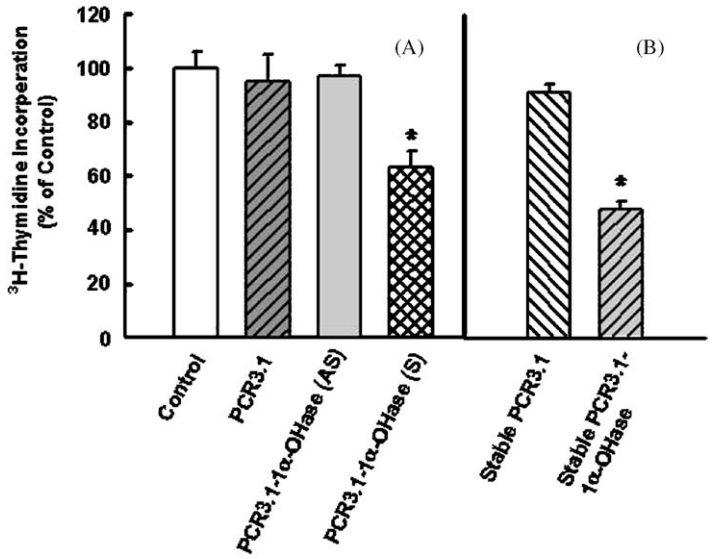

Fig. 3. Effect of 25-hydroxyvitamin D_3 [25(OH)D_3] (10^{-8}M) on the incorporation of ^{3}H-thymidine into DNA of LNCaP cells transfected with cDNA encoding 25(OH)D-1α-hydroxylase (1α-OHase). (a) LNCaP cells were transfected transiently with PCR 3.1 vector, antisens (AS) or sense (S) 1α-OHase cDNA. (b) LNCaP cells were stably transfected with either PCR 3.1 vector, or with sense 1α-OHase cDNA. Data are presented as % of mock transfected control in the absence of 25(OH)D_3. Data are mean ±SD, $n = 8$, $^*P < 0.05$. (Reproduced with permission, Whitlatch et al. 2002).

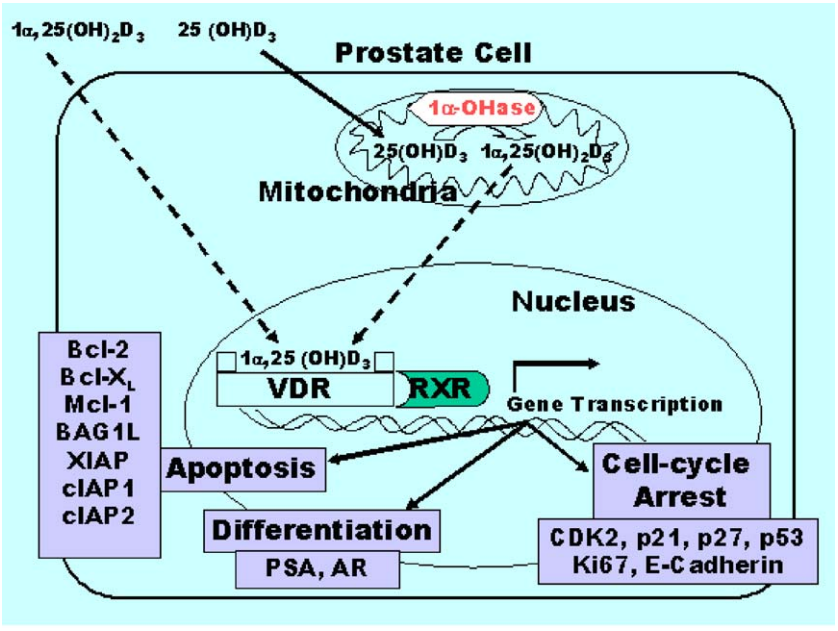

Fig. 4. 1,25(OH)$_2$D$_3$ regulates prostate cell growth by interacting with its nuclear vitamin D receptor (VDR) to alert the expression of genes that regulate cell cycle arrest, apoptosis, and differentiation. 25(OH)D is metabolized in the prostate cell to 1,25(OH)$_2$D which regulates cell growth.

synthesized on a commercial basis, the UV irradiation of foods was halted and vitamin D fortification was instituted. A wide variety of foods and drinks were fortified with vitamin D including milk, custard, soft drinks, bread, hot dogs and even beer (Holick, 2002b). After World War II, there was an outbreak of

hypercalcemia in infants in Great Britain that was found to be caused by the over fortification of milk with vitamin D resulting in vitamin D intoxication (British Pediatric Association, 1956). Because vitamin D analysis in foods was done as a bioassay that at times was unreliable, there was great concern in Great Britain and the rest of Europe about the potential for widespread vitamin D intoxication of infants that could lead to serious medical problems including mental retardation and kidney failure (Bauer and Freyberg, 1946; British Pediatric Association, 1956). As a result, laws were passed throughout Europe that forbid not only the fortification of milk and other dairy products with vitamin D, but also almost all foods and even skin creams with either vitamin D or its precursors. These regulations to forbid the fortification of most foods with vitamin D remain active in most European countries. However, the recognition that vitamin D deficiency is a health risk for children in Europe has resulted in many countries fortifying margarine and some cereals with vitamin D. A few countries have resurrected the fortification of milk with vitamin D including Sweden.

Vitamin D intoxication is caused by excessive ingestion for a prolonged period of time of super-pharmacologic doses of vitamin D. It is worth noting that sun exposure or exposure to ultraviolet radiation will not cause vitamin D intoxication because the ultraviolet radiation destroys any excess vitamin D that is produced (Holick, 2004a, b; Holick, 2002a, b).

Vitamin D intoxication is associated with a markedly elevated level of 25(OH)D and is accompanied with hypercalcemia, hyperphosphatemia and hypercalciuria. The Institute of Medicine in 1997 in the United States recommended that the safe upper limit for vitamin D intake for children under 1 year of age was 1000 IU/day and for adults 2000 IU/day. Vieth (1999) reported that healthy male adults who received 1000 or 4000 IU of vitamin D_3 a day for 2–5 months showed no signs of vitamin D intoxication, i.e. the serum and urinary calcium levels remained normal.

Vitamin D intoxication is an extremely rare occurrence and is often caused either intentionally or inadvertently because of either poor record keeping or human error. Some examples include the intentional or accidental mixing of sugar with vitamin D_3. The blood levels of 25(OH)D exceeded 3700 nmol/L, and was associated with hypercalcemia (Vieth et al., 2002). Koutkia et al. (2001a) reported a healthy male who was thought to be ingesting 2000 IU of vitamin D_3 from a powdered product. Unfortunately, the manufacturer forgot to dilute it, and therefore, he was ingesting 2 teaspoons of pure crystalline vitamin D_3 a day, which equaled more than 1 million units a day. His 25(OH)D was over 1250 nmol/L (500 ng/mL) and was associated with hypercalcemia. Typically, a 25(OH)D needs to be above 370 nmol/L (150 ng/mL) before the consequences of vitamin D intoxication, i.e. hypercalcemia and decrease in renal function are observed. People most sensitive to a high intake of vitamin D are those with mild to moderate renal failure or those who suffer from chronic granulomatous disorders such as sarcoidosis.

6. The development of vitamin D analogs for cancer treatment

The major stumbling block in developing vitamin D analogs for the treatment of cancer was the difficulty in separating the calcemic activity of vitamin D analogs from its antiproliferative activity. More than a thousand analogs of vitamin D have been made to date (Bouillon et al., 1995). Several analogs have been effectively used as antiproliferative agents for the treatment of psoriasis. However, to date, there has been scarcity of clinical trials demonstrating the therapeutic efficacy of vitamin D analogs. The one promising study was the observation that the vitamin D analog seocalcitol was effective in treating inoperable hepatocellular carcinoma (Dalhoff et al., 2003).

Recently, vitamin D analogs that have an additional side chain known as Gemini analogs have been found to be 100–1000 times more potent in their antiproliferative activity than the natural hormone. Studies in mice suggest that they may be useful in the treatment of some cancers including colon cancer (Spina et al., 2005).

7. Recommendations

Vitamin D deficiency is now recognized as a worldwide epidemic. Studies in the United States, Europe, India and Southeast Asia all reverberate the same theme, upwards of 50% of both children and adults are at high risk of vitamin D deficiency (Chapuy et al., 1997; Gordon et al., 2004; Kauppinen-Mäkelin et al., 2001; Kinyamu et al., 1998; Lips et al., 2001; Looker et al., 2002; Malabanan et al., 1998; Outila et al., 2001; Sullivan

et al., 2005). This is not at all surprising when it is appreciated that humans evolved in sunlight and like many other vertebrates, including non-human primates, have depended on sun exposure for their vitamin D requirement. Most humans on earth no longer are exposed to a sufficient amount of sunlight to satisfy their bodies' requirement for vitamin D. Barger-Lux et al. (1998) has suggested that the body uses between 3000 and 5000 IU of vitamin D_3 a day to satisfy all of its needs. Vitamin D supplementation is not widely practiced and most supplements only contain 400 IU of vitamin D. Most experts now agree that 1000 IU of vitamin D_3 is needed daily in the absence of sun exposure to maintain a healthy blood level of 25(OH)D of between 75 and 125 nmol/L (30–50 ng/mL) (Tangpricha et al., 2003).

Chuck et al. (2001) reported that a multivitamin supplement for nursing home residence in the UK was less effective than having the residents be exposed to ultraviolet radiation for maintaining adequate blood levels of 25(OH)D. For children and adults who have intestinal fat malabsorption syndromes, often sun exposure and exposure to ultraviolet B radiation from a light source is the only way they can obtain their vitamin D requirement (Koutkia et al., 2001b). Exposure to sensible sunlight and tanning bed radiation is also an effective way of maintaining healthy levels of 25(OH)D (Chel et al., 1998; Reid et al., 1985; Tangpricha et al., 2004).

There needs to be a recognition that sensible sun exposure followed by good sun protection, should be encouraged. Both the United States and Europe should consider increasing fortification of foods with vitamin D. In particular, in Europe there should be a resurrection of fortification of dairy products with vitamin D. In the United States and Europe, fortification of additional foods such as pasta will have important positive health ramifications that are likely to be similar to what was observed when pasta was fortified with folate to decrease the risk of birth defects.

8. Conclusion

The epidemic of vitamin D deficiency has both devastating consequences for bone health and insidious and deadly consequences for overall health and well-being (Heaney, 2003; Holick, 2004a, b; Holick, 2002a, b) (Fig. 5). The link between vitamin D deficiency (inadequate sun exposure) and increased mortality to cancer is

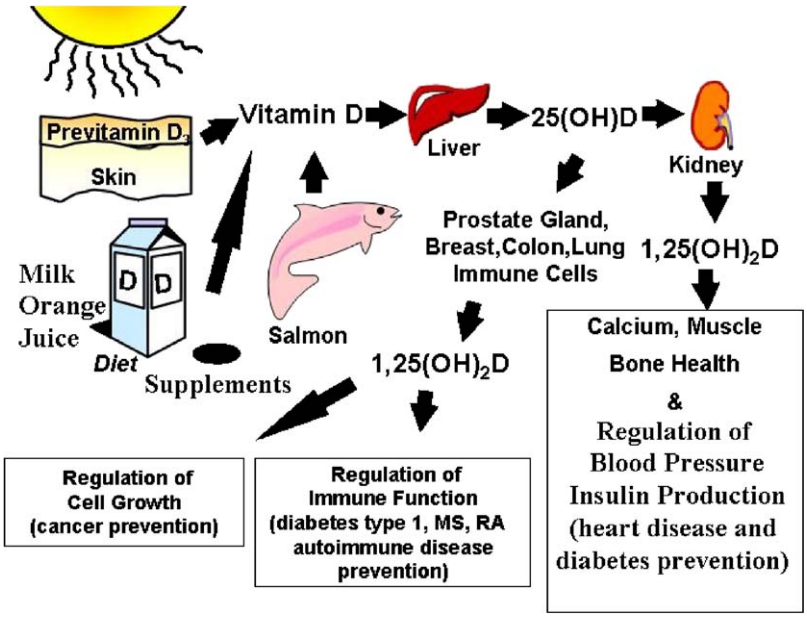

Fig. 5. Schematic representation of the multitude of other potential physiologic action of vitamin D for cardiovascular health, cancer prevention, regulation of immune function and decreased risk of autoimmune diseases. (Copyright Michael F. Holick, 2003, used with permission.)

now well established. The recent observation by Woo et al. (2005) shows that increasing vitamin D intake decreased prostate-specific antigen levels in men with metastatic prostate cancer should be the impetus to encourage increased intake of vitamin D worldwide. Vitamin D_3 is the preferred form of vitamin D because it is the natural form of vitamin D made in the skin and is approximately 50–80% more effective than vitamin D_2 in maintaining 25(OH)D levels. Children over the age of 1 year and all adults should receive 1000 IU of vitamin D_3 a day, or have sensible sun exposure to satisfy their vitamin D requirement. Measurement of $25(OH)D_3$ should be encouraged and should be party of an annual physical exam since there is no other method to determine vitamin D status of either a child or an adult.

Acknowledgements

This work was supported in part by NIH Grants: MOIRR00533, AR36963 and the UV Foundation.

References

Ahonen, M.H., Tenkanen, L., Teppo, L., Hakama, M., Tuohimaa, P., 2000. Prostate cancer risk and pre-diagnostic serum 25-hydroxyvitamin D levels (Finland). Cancer Causes Control 11, 847–852.

Apperly, F.L., 1941. The relation of solar radiation to cancer mortality in North America. Cancer Res 1, 191–195.

Barger-Lux, M.J., Heaney, R.P., Dowell, S., Chen, T.C., Holick, M.F., 1998. Vitamin D and its major metabolites: serum levels after graded oral dosing in healthy men. Osteoporosis Int 8 (3), 222–230.

Bauer, J.M., Freyberg, R.H., 1946. Vitamin D intoxication and metastatic calcification. J. Am. Med. Assoc. 130, 1208–1215.

Bertone-Johnson, E.R., Chen, W.Y., Holick, M.F., et al., 2005. Plasma 25-hydroxyvitamin D and 1,25-Dihydroxyvitamin D and risk of breast cancer. Cancer Epidemiol. Biomarkers Prev. 14, 1991–1997.

Bikle, D.D., Nemanic, M.K., Gee, E., Elias, P., 1986. 1,25-Dihydroxyvitamin D3 production by human keratinocytes: kinetics and regulation. J. Clin. Invest. 78, 557–566.

Bouillon, R., Okamura, W.H., Norman, A.W., 1995. Structure-function relationships in the vitamin D endocrine system. Endocrine Rev 16, 200–257.

British Pediatric Association, 1956. Hypercalcaemia in infants and vitamin D. Br. Med. J 45, 401.

Chapuy, M.C., Preziosi, P., Maamer, M., et al., 1997. Prevalence of vitamin D insufficiency in an adult normal population. Osteoporosis Int 7, 439–443.

Chel, V.G.M., Ooms, M.E., Popp-Snijders, C., et al., 1998. Ultraviolet irradiation corrects vitamin D deficiency and suppresses secondary hyperparathyroidism in the elderly. J. Bone Miner. Res. 13, 1238–1242.

Chen, T.C., Holick, M.F., 2003. Vitamin D and prostate cancer prevention and treatment. Trends Endocrinol. Metab. 14, 423–430.

Chuck, A., Todd, J., Diffey, B., 2001. Subliminal ultraviolet-B irradiation for the prevention of vitamin D deficiency in the elderly: a feasibility study. Photochem. Photoimmun. Photomed. 17 (4), 168–171.

Colston, K., Horst, M., Feldman, D., 1981a. Organ distribution of the cytoplasmic 1,25-dihydroxycholecalciferol receptor in various mouse tissues. Endocrinology 107, 1916.

Colston, K., Colston, M.J., Feldman, D., 1981b. 1,25-Dihydroxyvitamin D3 and malignant melanoma: the presence of receptors and inhibition of cell growth in culture. Endocrinology 108, 1083–1086.

Cross, H.S., Bareis, P., Hofer, H., et al., 2001. 25-hydroxyvitamin D_3-1-α-hydroxlyase and vitamin D receptor gene expression in human colonic mucosa is elevated during early carcinogenesis. Steroids 66, 287–292.

Dalhoff, K., Dancey, J., Astrup, L., et al., 2003. A phase II study of the vitamin D analogue Seocalcitol in patients with inoperable hepatocellular carcinoma. Br. J. Cancer 89, 252–257.

DeLuca, H., 2004. Overview of general physiologic features and functions of vitamin D. Am. J. Clin. Nutr. 80 (Suppl), 1689S–1696S.

Feldman, D., Zhao, X.Y., Krishnan, A.V., 2000. Editorial/Mini-review: vitamin D and prostate cancer. Endocrinology 141, 5–9.

Freedman, D.M., Dosemeci, M., McGlynn, K., 2002. Sunlight and mortality from breast, ovarian, colon, prostate, and non-melanoma skin cancer: a composite death certificate based case–control study. Occup. Environ. Med. 59, 257–262.

Garland, C., Shekelle, R.B., Barrett-Connor, E., Criqui, M.H., Rossof, A.H., Paul, O., 1985. Dietary vitamin D and calcium and risk of colorectal cancer: a 19-year prospective study in men. Lancet 1, 307–309.

Garland, C.F., Comstock, G.W., Garland, F.C., Helsing, K.J., Shaw, E.K., Gorham, E.D., 1989. Serum 25-hydroxyvitamin D and colon cancer: eight-year prospective study. Lancet 2, 1176–1178.

Garland, C.F., Garland, F.C., Gorham, E.D., 1991. Can colon cancer incidence and death rates be reduced with calcium and vitamin D? Am. J. Clin. Nutr. 54, 193S–201S.

Garland, F.C., Garland, C.F., Gorham, E.D., Young, J.F., 1990. Geographic variation in breast cancer mortality in the United States: a hypothesis involving exposure to solar radiation. Prev. Med. 19, 614–622.

Gordon, C.M., DePeter, K.C., Feldman, H.A., Grace, E., Emans, S.J., 2004. Prevalence of vitamin D deficiency among healthy adolescents. Arch. Pediatr. Adolesc. Med. 158, 531–537.

Grant, W.B., 2002a. An ecologic study of the role of solar UV-B radiation in reducing the risk of cancer using cancer mortality data, dietary supply data and latitude for European countries. In: Holick, M.F. (Ed.), Biologic Effects of Light 2001 Proceedings of a Symposium, Boston, MA. Kluwer Academic Publishing, Boston, pp. 267–276.

Grant, W.B., 2002b. An estimate of premature cancer mortality in the US due to inadequate doses of solar ultraviolet-B radiation. Cancer 94, 1867–1875.

Grant, W.B., 2004. A multicountry ecologic study of risk and risk reduction factors for prostate cancer mortality. Eur. Urol. 45, 271–279.

Grant, W.B., Holick, M.F., 2005. Benefits and requirements of vitamin D for optimal health: a review. Alter. Med. Rev. 10, 94–111.

Hanchette, C.L., Schwartz, G.G., 1992. Geographic patterns of prostate cancer mortality. Cancer 70, 2861–2869.

Heaney, R.P., 2003. Invited award lecture: long latency deficiency disease—insights from calcium and vitamin D. Am. J. Clin. Nutr. 78, 912–919.

Holick, M.F., 1998. Clinical efficacy of 1,25-dihydroxyvitamin D_3 and its analogues in the treatment of psoriasis. Retinoids 14, 7–12.

Holick, M.F., 2002a. Vitamin D. The underappreciated D-lightful hormone that is important for skeletal and cellular health. Curr. Opin. Endocrinol. Diabetes 9, 87–98.

Holick, M.F., 2002b. Vitamin D: Importance for bone health, cellular health and cancer prevention. In: Holick, M.F. (Ed.), Biologic Effects of Light 2001 Proceedings of a Symposium, Boston, MA. Kluwer Academic Publishing, Boston, pp. 155–173.

Holick, M.F., 2004a. Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. Am. J. Clin. Nutr. 80, 1678S–1688S.

Holick, M.F., 2004b. Vitamin D: importance in the prevention of cancers, type 1 diabetes, heart disease, and osteoporosis. Am. J. Clin. Nutr. 79, 362–371.

Janowsky, E.C., Lester, G.E., Weinberg, C.R., et al., 1999. Association between low levels of 1,25-dihydroxyvitamin D and breast cancer risk. Public Health Nutr. 2, 283–291.

John, E.M., Schwartz, G.G., Dreon, D.M., Koo, J., 1999. Vitamin D and breast cancer risk: the NHANES I epidemiologic follow-up study, 1971–1975 to 1992. National Health and Nutrition Examination Survey. Cancer Epidemiol. Biomarkers. Prev. 8, 399–406.

Kauppinen-Mäkelin, R., Tähtelä, R., Löyttyniemi, E., Kärkkäinen, J., Välimäki, M.J., 2001. High prevalence of hypovitaminosis D in Finnish medical in- and outpatients. J. Intern. Med. 249, 559–563.

Khosla, S., 2001. The OPG/RANKL/RANK system. Endocrinology 142 (12), 5050–5055.

Kinyamu, H.K., Gallagher, J.C., Rafferty, K.A., Balhorn, K.E., 1998. Dietary calcium and vitamin D intake in elderly women: Effect on serum parathyroid hormone and vitamin D metabolites. Am. J. Clin. Nutr. 67, 342–348.

Koeffler, H.P., Hirjik, J., Iti, L., 1985. Southern California Leukemia Group.1,25-dihydroxyvitamin D_3: in vivo and vitro effects on human pre-leukemic and leukemic cells. Cancer Treat. Rep. 69, 1399–1407.

Koutkia, P., Lu, Z., Chen, T.C., Holick, M.F., 2001a. Treatment of vitamin D deficiency due to Crohn's disease with tanning bed ultraviolet B radiation. Gastroenterology 121 (6), 1485–1488.

Koutkia, P., Lu, Z., Chen, T.C., Holick, M.F., 2001b. Treatment of vitamin D deficiency due to Crohn's disease with tanning bed ultraviolet B radiation. Gastroenterology 121, 1485–1488.

Lefkowitz, E.S., Garland, C.F., 1994. Sunlight, vitamin D, and ovarian cancer mortality rates in US women. Int. J. Epidemiol. 23, 1133–1136.

Lips, P., Duong, T., Oleksik, A., et al., 2001. A global study of vitamin D status and parathyroid function in postmenopausal women with osteoporosis: baseline data from the multiple outcomes of raloxifene evaluation clinical trial. J. Clin. Endocrinol. Metab. 86, 1212–1221.

Looker, A.C., Dawson-Hughes, B., Calvo, M.S., Gunter, E.W., Sahyoun, N.R., 2002. Serum 25-hydroxyvitamin D status of adolescents and adults in two seasonal subpopulations from NHANES III. Bone 30, 771–777.

Luscombe, C.J., Fryer, A.A., French, M.E., et al., 2001. Exposure to ultraviolet radiation: association with susceptibility and age at presentation with prostate cancer. Lancet 358, 641–642.

MacLaughlin, J., Gange, W., Taylor, D., Smith, E., Holick, M.F., 1985. Cultured psoriatic fibroblasts from involved and uninvolved sites have a partial, but not absolute resistance to the proliferation-inhibition activity of 1,25-dihydroxyvitamin D_3. Proc. Natl. Acad. Sci. USA 52, 5409–5412.

Malabanan, A., Veronikis, I.E., Holick, M.F., 1998. Redefining vitamin D insufficiency. Lancet 351, 805–806.

Mawer, E.B., Hayes, M.E., Heys, S.E., et al., 1994. Constitutive synthesis of 1,25-dihydroxyvitamin D3 by a human small cell lung cell line. J. Clin. Endocrinol. Metab. 79, 554–560.

Norman, A.W., Bishop, J.E., Bula, C.M., et al., 2002. Molecular tools for study of genomic and rapid signal transduction responses initiated by 1α 25$(OH)_2$-vitamin D_3. Steroids 67, 457–466.

Omdahl, J., Morris, H., May, B., 2002. Hydroxlyase enzymes of the vitamin D pathway: expression, function and regulation. Annu. Rev. Nutr. 22, 139–166.

Outila, T.A., Karkkainen, M.U., Lamberg-Allardt, C.J., 2001. Vitamin D status affects serum parathyroid hormone concentrations during winter in female adolescents: associations with forearm bone mineral density. Am. J. Clin. Nutr. 74, 206–210.

Reid, I.R., Gallagher, D.J.A., Bosworth, J., 1985. Prophylaxis against vitamin D deficiency in the elderly by regular sunlight exposure. Age Ageing 15, 35–40.

Schwartz, G.G., Whitlatch, L.W., Chen, T.C., Lokeshwar, B.L., Holick, M.F., 1998. Human prostate cells synthesize 1,25-dihydroxyvitamin D_3 from 25-hydroxyvitamin D_3. Cancer Epidemiol. Biomarkers Prev. 7, 391–395.

Skowronski, R.J., Peehl, D.M., Feldman, D., 1993. Vitamin D and prostate cancer: 1,25-Dihydroxyvitamin D3 receptors and actions in human prostate cancer cell lines. Endocrinology 132, 1952–1960.

Spina, C., Tangpricha, V., Yao, M., Zhou, W., Wolfe, M.M., Maehr, H., Uskokovic, M., Adorini, L., Holick, M.F., 2005. Colon cancer and solar ultraviolet B radiation and prevention and treatment of colon cancer in mice with vitamin D and its Gemini analogs. J. Steroid Biochem. Mol. Biol. 97, 111–120.

Stumpf, W.E., Sar, M., Reid, F.A., et al., 1979. Target cells for 1,25-dihydroxyvitamin D3 in intestinal tract, stomach, kidney, skin, pituitary, and parathyroid. Science 206, 1188–1190.

Suda, T., Abe, E., Miyaura, C., et al., 1982. Induction of differentiation of human myeloid leukemia cells by 1 α,25-dihydroxyvitaminD3. In: Norman, A., Schaefer, K., Herrath, D.V., Grigdeit, H.-G. (Eds.), Vitamin D: Chemical, Biochemical and Clinical Endocrinology of Calcium Metabolism. Walter de Gruyter, New York, pp. 59–64.

Sullivan, S.S., Rosen, C.J., Halteman, W.A., Chen, T.C., Holick, M.F., 2005. Adolescent girls in Maine at risk for vitamin D insufficiency. J. Am. Diet. Assoc. 105, 971–974.

Tanaka, H., Abe, E., Miyaura, C., et al., 1982. 1 alpha,25-Dihydroxycholecalciferol and human myeloid leukemia cell line (HL-60): the presence of cytosol receptor and induction of differentiation. Biochem. J. 204, 713–719.

Tangpricha, V., Flanagan, J.N., Whitlatch, L.W., et al., 2001. 25-Hydroxyvitamin D-1α-hydroxylase in normal and malignant colon tissue. Lancet 357, 1673–1674.

Tangpricha, V., Koutkia, P., Rieke, S.M., Chen, T.C., Perez, A.A., Holick, M.F., 2003. Fortification of orange juice with vitamin D: a novel approach to enhance vitamin D nutritional health. Am. J. Clin. Nutr. 77, 1478–1483.

Tangpricha, V., Turner, A., Spina, C., Decastro, S., Chen, T., Holick, M.F., 2004. Tanning is associated with optimal vitamin D status (serum 25-hydroxyvitamin D concentration) and higher bone mineral density. Am. J. Clin. Nutr. 80, 1645–1649.

Tangpricha, V., Spina, C., Yao, M., Chen, T.C., Wolfe, M.M., Holick, M.F., 2005. Vitamin D Deficiency enhances the growth of MC-26 colon cancer xenografts in Balb/c mice. J. Nutr. 135, 2350–2354.

Tangrea, J., Helzlsouer, K., Pietinen, P., et al., 1997. Serum levels of vitamin D metabolites and the subsequent risk of colon and rectal cancer in Finnish men. Cancer Causes Control 8, 615–625.

Vieth, R., 1999. Vitamin D supplementation, 25-hydroxyvitamin D concentrations, and safety. Am. J. Clin. Nutr. 69, 842–856.

Vieth, R., 2005. The pharmacology of vitamin D, including fortification strategies. In: Feldman, D., Pike, J.W., Glorieux, F.H. (Eds.), Vitamin D, second ed. Elsevier Acad. Press, Amsterdam (Chapter 61).

Vieth, R., Pinto, T.R., Reen, B.S., Wong, M.M., 2002. Vitamin D poisoning by table sugar. Lancet 359, 672.

Whitlatch, L.W., Young, M.V., Schwartz, G.G., et al., 2002. 25-hydroxyvitamin D-1-α-hydroxylase activity is diminished in human prostate cancer cells and is enhanced by gene transfer. J. Steroid Biochem. Mol. Biol. 81, 135–140.

Woo, T.C., Choo, R., Jamieson, M., Chander, S., Vieth, R., 2005. Pilot study: potential role of vitamin D (Cholecalciferol) in patients with PSA relapse after definitive therapy. Nutr. Cancer 51 (1), 32–36.

Zhao, X.Y., Feldman, D., 2001. The role of vitamin D in prostate cancer. Steroids 66, 293–300.