Unravelling of hidden secrets: the role of vitamin D in skin aging

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The skin is the only tissue in the human body that represents both a target tissue for biologically active vitamin D compounds including 1,25-dihydroxyvitamin D (1,25(OH)2D) and has the capacity for the synthesis of 1,25(OH)2D from 7-dehydrocholesterol (7-DHC). Recent findings indicate that the vitamin D endocrine system (VDES), besides multiple other important functions, regulates aging in many tissues, including skin. This concept is strongly supported by several independent studies in genetically modified mice (including FGF23-/- and Klotho-/- mice) that are characterized by altered mineral homeostasis caused by a high vitamin D activity. These mice typically have phenotypic features of premature aging that include, besides short lifespan, retarded growth, ectopic calcification, immunological deficiency, osteoporosis, atherosclerosis, hypogonadism, skin and general organ atrophy. Notably, it has been demonstrated that these phenotypic features can be reversed by normalizing mineral homeostasis and/or vitamin D status. Interestingly, the aging phenotypes of mice suffering from hypovitaminosis D (VDR-/- and CYP27B1-/- mice) are quite similar to those suffering from hypervitaminosis D (including FGF23-/- and Klotho-/- mice). Consequently, it has been hypothesized that thus, both hypo- and hyper-vitaminosis D may enhance aging. Aging seems to show a U-shaped response curve to vitamin D status, and, therefore normovitaminosis D seems to be important for preventing premature aging. Additionally, laboratory investigations have now convincingly shown that vitamin D compounds protect the skin against the hazardous effects of various skin aging-inducing agents, including UV (UV) radiation. In conclusion, these findings support the concept that UV-radiation exerts both skin aging-promoting and -inhibiting effects, the latter via induction of cutaneous vitamin D synthesis. Future studies will clarify the effect of vitamin D compounds on expression and function of potential key regulators of skin aging, such as TAp63 or the IGF-1 signaling pathway. Furthermore, the efficacy of topically applied vitamin D compounds in the prevention of skin aging has to be evaluated in future clinical trials.

Introduction

In recent years, there was an extensive search for the “fountain of youth,” that means for pharmacologic agents effective in preventing tissue aging. Although the “fountain of youth” has still not been found, there is at present still enormous interest in identifying pharmacologic agents that may prevent skin aging. Recent findings indicate that the vitamin D endocrine system (VDES), besides many other important functions, regulates aging in many tissues, including skin. In this review, I summarize our present understanding of the role of the VDES for skin aging and demonstrate that vitamin D compounds represent interesting candidates for the prevention of skin aging.

The Vitamin D Endocrine System

It is well known that vitamin D, the precursor of the biologically active vitamin D metabolite 1,25-dihydroxyvitamin D (1,25(OH)2D, calcitriol) can be obtained from the diet or synthesized in the skin under the influence of UV-B radiation from 7-dehydrocholesterol (7-DHC).1-3 It has been estimated that under present living conditions in most countries in Europe and US, appr. 90% of the needed vitamin D must be synthesized in the skin and only about 10% are taken up by the diet.1-3 The skin is the only tissue in the human body that represents both a target tissue for biologically active vitamin D compounds including 1,25(OH)2D3 and has the capacity for the synthesis of 1,25(OH)2D3 from 7-DHC.1-3 Several enzymatic reactions are involved in the photochemical cutaneous synthesis of vitamin D, hereunder 4 photoreversible reactions and one non reversible phototransformation.1-3 While vitamin D3 (ergocalciferol) can be found in plants, vitamin D3 (cholecalciferol) is photochemically synthesized under the influence of UVB radiation in the skin of animals and humans.1-3 The biologically active vitamin D metabolite 1,25(OH)2D3, that circulates in the blood, is synthesized from vitamin D by a well characterized biochemical reaction cascade.1-3 First, it is hydroxylated in the liver in C-25 position by cytochrome P450 enzymes, including the vitamin D-25-hydroxylase (CYP27A1) and CYP2R1, before it gets hydroxylated a second time in the kidney in C-1 position by another cytochrome P450 enzyme, the renal 25-hydroxyvitamin D-1α-hydroxylase (CYP27B1).1-3

The production of 1,25(OH)2D3 in the kidney is regulated by a feedback-mechanism of the hormone itself, as well as by parathyroid hormone, calcium and cytokines like Interferon γ (IFNγ) or tumor necrosis factor α (TNFα).1-3 Until the last decades of the last century, it was concluded that the kidney was the sole source of 1,25(OH)2D3 production. However, more...
This may represent an important mechanism, protecting keratinocytes and other cells against the UV-B-induced synthesis of reactive oxygen radicals.

Moreover, 1,25(OH)2D3 protects skin cells against apoptosis by induction of many anti-apoptotic proteins including Bcl-2 and activation of the MEK/ERK- and PI-3K/Akt-metabolic pathways. 1,25(OH)2D is able to induce the neutral Mg2+-dependent sphingomyelinase, which hydrolyses sphingomyelin to ceramide.13 Interestingly, ceramide stimulates the prodifferentiating effect from 1,25(OH)2D on keratinocytes.14 Moreover, it plays an important role in the induction of apoptosis in a variety of cells, including keratinocytes.14,15 It has been demonstrated that physiological concentrations of 1,25(OH)2D in keratinocyte cultures do not induce apoptosis. To the contrary, physiological concentrations of 1,25(OH)2D generate an apoptosis-resistance against ceramides, UV radiation and tumor necrosis factor-α (TNF-α).15 The cytoprotective/anti-apoptotic effect of 1,25(OH)2D is obviously linked to the development of sphingosine-1-phosphate. This is also clarified by the fact that the antiapoptotic effect of 1,25(OH)2D can be completely suppressed by addition of the sphingosinkinase-inhibitor N,N-dimethylsphingosine.15 In contrast, pharmacological concentrations of 1,25(OH)2D (≥10−6 M) do induce apoptosis. Similar effects have been observed in the regulation of keratinocyte-growth, where, as outlined above, physiological concentrations of 1,25(OH)2D (around 10−11 M) stimulate cell proliferation, whereas high pharmacological concentrations of 1,25(OH)2D have a dose-dependent antiproliferative effect.16

In line with these findings, we have recently used colony-forming-unit culture proliferation assays to prove that pretreatment with 1,25(OH)2D (10−7 M for 48 h) protects human keratinocytes against the hazardous effects of a single irradiation with 100 J/cm2 UV-B.9 In this study, the number of cell colonies counted after a growth period for 7 d post radiation was twice as high in 1,25(OH)2D-pretreated cells as compared with controls that were not treated with 1,25(OH)2D.9 Furthermore, using WST-1- and crystal violet-based proliferation assays, it could be demonstrated that 1,25(OH)2D (10−7 M) has a protective effect after irradiation of keratinocytes with ascending doses of UV-B (100 J/cm2-1000 J/cm2).9

It is well recognized that the photocarcinogenesis of non-melanoma skin cancer is mainly due to mutations resulting from insufficient repaired DNA-photoproducts.17 The most established DNA-photoproducts caused by UV radiation are cyclobutane pyrimidine dimers (CPDs).9,17 Recent laboratory investigations show that treatment with 1,25(OH)2D reduces the number of CPDs in human keratinocytes after UVB-radiation.9,18 A study from Gupta et al. describes a reduction of the number of CPDs after a pretreatment with 1,25(OH)2D (10−7 M) followed by an irradiation of the cells with 200 mJ/cm2 UV-B, as compared with controls that were not treated with 1,25(OH)2D.18 In line with these results, Trémezaygues et al. demonstrated that pretreatment of keratinocytes with 1,25(OH)2D (10−7 M) has a protective effect on the cells, even after irradiation with higher doses of UV-B (100 J/cm2 and 1000 J/cm2).9 Complementing the results of Gupta et
al., Trémezaygues et al. showed that pretreatment of HaCaT-keratinocytes with 1,25(OH)₂D results not only in a reduction of the number of formed CPDs but also in a subsequent quicker reduction in number of CPDs, as compared with controls that were not treated with 1,25(OH)₂D.⁹

Regarding the influence of vitamin D metabolites on the development of ionizing radiation damage, several investigations were performed during the last years.⁶⁹ A characteristic feature of cellular damage induced by ionizing radiation are DNA double strand breaks (DSB). The histone protein H2AX is phosphorylated in position 139 at the carboxyterminus as an answer to a double strand break – the result is γH2AX. This phosphorylated histone protein supports a recruitment and retention of various repair proteins at the site of the DSB. It can therefore be considered as a marker for DSBs. Recent studies show a decreased immunoreactivity for γH2AX caused by ionizing radiation after pretreatment of cells with 1,25(OH)₂D (10⁻⁷ M).⁹

Interestingly, it has been demonstrated that photoprotection by 1,25-dihydroxyvitamin D is associated by an increase in p53 and a decrease in nitric oxide products.¹⁸ Both members of the p53 family and nitric oxide have been implicated to be of importance for skin aging.¹⁹-²¹

To put it in a nutshell, the current literature convincingly supports the concept of a cytoprotective effect of 1,25(OH)₂D against the damaging effects of UV and other agents, which may help to prevent premature skin aging. The clinical potential of this protective effect has to be elucidated in future clinical trials.

Vitamin D Status and Skin Aging: Animal Studies in Genetically Modified Mice Provide Evidence for a U-shaped Curve

The concept that the VDES, besides many other important functions, regulates aging in skin and many other tissues, is strongly supported by several independent studies in genetically modified mice (including FGF-23-/- and Klotho-/- mice that develop altered mineral homeostasis caused by a high vitamin D activity).²²-²⁵ These mice typically have phenotypic features of premature aging that include, besides short lifespan, skin and general organ atrophy, retarded growth, ectopic calcification, immunological deficiency, osteoporosis, atherosclerosis, and hypogonadism.²²-²⁵ Notably, it has been demonstrated that these phenotypic features can be reversed by normalizing mineral homeostasis (by a rescue diet containing high calcium and phosphate) and/or vitamin D.²²-²⁵ Interestingly, the aging phenotypes of mice suffering from hypovitaminosis D (VDR-/- and CYP27B1-/- mice) are quite similar to those suffering from hypervitaminosis D (including FGF-23-/- and Klotho-/- mice).²²,²⁴ VDR-/- mice are characterized by skin thickening and wrinkling, alopecia, have growth retardation, osteoporosis, kyphosis, ectopic calcification, progressive loss of hearing and balance as well as a relatively short lifespan.²²,²⁴ Consequently, it has been hypothesized that thus, both hypo- and hypervitaminosis D may enhance aging and that aging seems to show a U-shaped response curve to vitamin D status, and, therefore normovitaminosis D seems to be important for preventing premature aging.²²,²⁴

Vitamin D Status and Skin Aging: What Are the Molecular Mechanisms by Which Vitamin D Signaling Feeds the “Fountain of Youth”? It has to be noted that at present, the molecular mechanisms that underly the anti-aging effects of vitamin D compounds are not well understood. Based upon many investigations, including cDNA microarray analysis of mRNAs, as many as 500–1000 genes are estimated to be regulated by VDR ligands.²⁵,²⁷ Many of these 1,25(OH)₂D-regulated genes that are relevant for healthy aging of the skin and other tissues are calcemic, phosphatemic, or affect bone remodelling.²⁵ It has convincingly been outlined in a review by Mark Haussler et al. that the VDES controls the expression of at least 11 genes (osteonectin or SPPI, TRPV6, LRP5, BGP, RANKL, OPG, CYP24A1, PTH, FGF-23, PHEX, and klotho) which encode bone and mineral homeostasis effectors that also facilitate aging well.²⁵ To govern these 1,25(OH)₂D-induced phenomena, there exists a separate class of feedback regulatory genes which curtail the mineralotropic and osteotrophic actions of 1,25(OH)₂D.²⁵ Control of these genes by VDR delimits bone mineralization to the defined endoskeleton, prevents ectopic calcification elicited by excesses of either calcium or phosphate, reduces age-related vascular pathology and atherosclerosis, protects against muscle and skin atrophy as well as respiratory failure, and generally prevents premature aging and lengthens lifespan.²³,²⁵ Many of these pathologies are also the result of hypervitaminosis D.²³,²⁵ Consequently, it has been hypothesized that excess vitamin D and its actions actually may reduce lifespan, meaning that the level of 1,25(OH)₂D as well as the sequelae of its effects through VDR must be “detoxified” and sustained in an optimal range to maintain healthful aging.²³,²⁵

Interestingly, the association of vitamin D-deficiency with some types of cancer has been convincingly demonstrated and both aging and cancer are promoted by some similar molecular mechanisms.²⁷ As an example, damage on DNA and telomeres cause both aging and cancer, involving the tumor suppressor protein, p53. Moreover, the insulin-like growth factor (IGF-1) and FGF-23 signaling pathways regulate growth, aging and cancer. Interestingly, the VDES has been shown to regulate these important signaling pathways. Mutations in insulin/IGF-1 signaling pathway have been shown to lead to increased longevity in various invertebrate models, although it has to be noted that it was recently shown that the Igf1r(-/-) mouse is not a model of increased longevity and delayed aging as predicted by invertebrate models with mutations in the insulin/IGF-1 signaling pathway.²⁸

The p53 gene family, NF-κB and telomerase reverse transcriptase (TERT) might be important molecular targets mediating vitamin D action in aging and cancer.²⁹,³⁰ Since the discovery of the TP63 gene in 1998, many studies have demonstrated that ΔNp63, a p63 isoform of the p53 gene family, is involved in multiple functions during skin development and in adult stem/progenitor cell regulation.²⁹,³⁰ Interestingly, a recent investigation demonstrated novel functions for TAp63 indicating a protective role of TAp63 on premature aging.²⁹,³⁰ TAp63 controls skin homeostasis by maintaining dermal and epidermal progenitor/stem cell pool and protecting them from senescence,
DNA damage and genomic instability. Recently, a TAP63 conditional knockout mouse was developed and used to ablate TAP63 in the germline (TAP63(-/-)) or in K14-expressing cells in the basal layer of the epidermis (TAP63(fl/fl);K14cre+). Interestingly, TAP63(-/-) mice age prematurely and develop blisters, skin ulcerations, senescence of hair follicle-associated dermal and epidermal cells, and decreased hair morphogenesis. These data indicate that TAP63 maintains adult skin stem cells by regulating cellular senescence and genomic stability, thereby preventing premature skin aging.

Another interesting observation that may be of high importance for skin aging is the link of the VDES to detoxification. Evolutionarily, the VDR is closely related to the pregnane X receptor (FXR) which regulates xenobiotic biotransformation and to the farnesoid X receptor (FXR) which regulates bile acid metabolism. In line with this finding, the ancient function of VDR in choridates is considered to be that of detoxification. It can be speculated whether VDR-induced detoxification may represent an important mechanism to prevent aging in various tissues, including skin.

Conclusions

It can be summarized that the VDES influences skin aging via a broad variety of different mechanisms, that include protection against UV-induced cellular damage, detoxification, and regulation of genes important for cellular aging. The efficacy of topically applied vitamin D compounds and of a healthy vitamin D status for the prevention of skin aging has to be evaluated in future clinical trials.

References


