Dermato-Endocrinology 4:3, 241–244; July–December 2012; © 2012 Landes Bioscience

Unravelling of hidden secrets
The role of vitamin D in skin aging

Jörg Reichrath

Klinik für Dermatologie; Venerologie und Allergologie; Universitätsklinikum des Saarlandes; Homburg/Saar, Germany

Keywords: vitamin D, 25-hydroxyvitamin D, vitamin D receptor, fountain of youth, skin, aging, skin aging

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$(OH)_2$D] and has the capacity for the synthesis of 1,25$(OH)_2$D 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 FGF-23$^{-/-}$ and Klotho$^{-/-}$ mice). Consequently, it has been hypothesized that thus, both hypo- and hypervitaminosis 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 ultraviolet (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.

Correspondence to: Jörg Reichrath; Email: Joerg.reichrath@uks.eu
Submitted: 12/30/11; Accepted: 06/29/12
http://dx.doi.org/10.4161/de.21312

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$(OH)_2$D, 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$(OH)_2D_3$ and has the capacity for the synthesis of 1,25$(OH)_2D_3$ 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 D_2 (ergocalciferol) can be found in plants, vitamin D_3 (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$(OH)_2$D, 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$(OH)_2D_3$ 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 $1,25(OH)_2D_3$ production. However, more recent investigations demonstrated that many cell types including human keratinocytes, monocytes, macrophages osteoblasts, prostate and colon cells, express the enzymatic machinery for the synthesis of $1,25(OH)_2D_3$ (i.e., CYP27B1), and are able to synthesize $1,25(OH)_2D_3$.[1,3] In keratinocytes, studies could prove the presence of 1α-hydroxylase (CYP27A1) and 25-hydroxylase (CYP27B1).[3] According to these findings, the keratinocyte is the only cell type known until today, that is able to synthesize $1,25(OH)_2D_3$ from 7-DHC.[3]

The metabolism of $1,25(OH)_2D$, circulating in the blood and present in various tissues, to calcitroic acid results from another well characterized biochemical reaction cascade. The reduction of $1,25(OH)_2D_3$ to 24,25-dihydroxycholecalciferol in the kidney (and in other tissues) and consecutive reactions are effectuated by another cytochrome P450 enzyme, the 1,25-dihydroxyvitamin D-24-hydroxylase (CYP24A1).[1] 24,25-dihydroxycholecalciferol has only a slight biological activity. According to present knowledge $1,25(OH)_2D$ has a 100 to 1000-fold higher biological activity as compared with other natural vitamin D metabolites.[1]

$1,25(OH)_2D$ exerts at least many of its biologic effects via binding to the nuclear vitamin D receptor (VDR).[1] VDR is a member of the thyroid hormone and retinoic acid receptor subfamily of nuclear hormone receptors that bind to specific response elements in target genes following heterodimerization with retinoid X receptor (RXR) isoforms.[1] VDR regulates the expression of genes encoding factors which control important cellular functions implicated in skin aging, including proliferation, differentiation, metabolism, ion transport, apoptosis, and detoxification.[1]

Vitamin D Compounds Protect the Skin Against the Hazardous Effects of Various Skin Aging-Inducing Agents, Including Ultraviolet (UV) Radiation

It is well accepted in the scientific community that vitamin D compounds protect the skin against the hazardous effects of many skin aging-inducing agents, including ultraviolet (UV) radiation.[4-11] Concerning protection against UV-B-induced cellular damage,[4-11] the underlying mechanisms are manifold and at least in part associated with the suppression of UV-B-induced apoptosis.[6-9] However, it has to be noted that it depends on many other factors whether effects of $1,25(OH)_2D$ on UV-induced apoptosis are beneficial or negative for the human body.[9] In in vitro investigations using an ELISA that detects DNA-fragmentation, it was demonstrated that pretreatment of keratinocytes with $1,25(OH)_2D$ (1 μM) over 24 h suppresses UV-B-induced apoptosis up to 55–70%, and reduces the mitochondrial cytochrome c release, one of the markers of UV-B-induced apoptosis, up to 90%.[6-9] Two important mediators of the UV-response in keratinocytes, namely the activation of a Jun-NH_2-terminal kinase and the production of interleukin-6, are also reduced about 30% respective 75–90% by a pretreatment with $1,25(OH)_2D$ (1 μM).[6-8] Moreover, the UV-B-induced cleavage of the Poly-(ADP-Ribose)-Polymerase (PARP) is inhibited, and methallothionein (MT)-mRNA is induced after pretreatment of keratinocytes with $1,25(OH)_2D$ (1 μM for 24 h).[6-8] MT is an antioxidans and acts as a radical catcher after UV-radiation.[6-9,12] This may represent an important mechanism, protecting keratinocytes and other cells against the UV-B-induced synthesis of reactive oxygen radicals.

Moreover, $1,25(OH)_2D_3$ 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 Mg^{2+}-dependent sphingomyelinase, which hydrolyses sphingomyelin to ceramid.[13] Interestingly, ceramid 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 TNFα.[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 $1,25(OH)_2D$ ($\geq 10^{-6}$ 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 (100–1000 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 UV-B-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^{-9} 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.[4,9] A characteristic feature of cellular damage induzed 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 recruition 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.[25,26] 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 (osteopontin or SPP1, 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 curb 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, NFκB 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.[29,30]

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+).[29,30] Interestingly, TAp63$^{(-/-)}$ mice age prematurely and develop blisters, skin ulcerations, senescence of hair follicle-associated dermal and epidermal cells, and decreased hair morphogenesis.[29,30] These data indicate that TAp63 maintains adult skin stem cells by regulating cellular senescence and genomic stability, thereby preventing premature skin aging.[29,30]

Another interesting observation that may be of high importance for skin aging is the link of the VDES to detoxicification.[25] Evolutionarily, the VDR is closely related to the pregnane X receptor (PXR) that modulates xenobiotic detoxification and to the farnesoid X receptor (FXR) which regulates bile acid metabolism.[25] In line with this finding, the ancient function of VDR in chordates is considered to be that of detoxification.[25] This property has apparently been retained in extant mammals as evidenced by the ability of the VDR to bind carcinogenic secondary bile acid, lithocholic acid (LCA), with low affinity and stimulate its detoxification in colon via induction of CYP3A4 and SULT2.[25] 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.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

References

1. Holick MF. Vitamin D deficiency. N Engl J Med 2007; 357:266-81; PMID:17634462; http://dx.doi.org/10.1056/NEJMra070553
2. Reichrath J. The challenge resulting from positive and negative effects of sunlight: how much solar UV exposure is appropriate to balance between risks of vitamin D deficiency and skin cancer? Prog Biophys Mol Biol 2006; 92:9-16; PMID:16603232; http://dx.doi.org/10.1016/j.pbiomolbio.2006.02.010
3. Reichrath J. Vitamin D and the skin: an ancient friend, revisited. Exp Dermatol 2007; 16:618-25; PMID:17576242; http://dx.doi.org/10.1111/j.1600-0625.2007.00570.x
4. Trémezaygues L, Sticherling M, Pföhler C, Friedrich M, Meineke V, Seifert M, et al. Cutaneous photosynthesis of vitamin D: an evolutionary highly-conserved endocrine system that protects against environmental hazards including UV-radiation and microbial infections. Anticancer Res 2006; 26(4A):2743-8; PMID:16886686
5. Lee JH, Youn JI. The photoprotective effect of 1,25-dihydroxyvitamin D3 on ultraviolet light B-induced damage in keratinocyte and its mechanism of action. J Dermatol Sci 1998; 18:11-8; PMID:9747657; http://dx.doi.org/10.1016/S0923-1811(98)00015-2
6. De Haes P, Garmyn M, Degreef H, Vantieghem K, Bouillon R, Segaert S. 1,25-Dihydroxyvitamin D3 inhibits ultraviolet B-induced apoptosis, Jun kinase activation, and interleukin-6 production in primary human keratinocytes. J Cell Biochem 2003; 89:663-73; PMID:12858333; http://dx.doi.org/10.1002/jcb.10540
7. De Haes P, Garmyn M, Verstuyf A, De Clercq P, Vandewalle M, Vantieghem K, et al. Two 14-epi analogues of 1,25-dihydroxyvitamin D_3 protect human keratinocytes against the effects of UVB. Arch Dermatol Res 2004; 295:527-34; PMID:15042383; http://dx.doi.org/10.1007/s00403-004-0451-x
8. De Haes P, Garmyn M, Verstuyf A, De Clercq P, Vandewalle M, Degreef H, et al. 1,25$(OH)_2D_3$ and analogues protect primary human keatinocytes against UVB-induced DNA damage. J Photochem Photobiol 2005; 78:141-8; http://dx.doi.org/10.1016/j.jphotobiol.2004.09.010
9. Trémezaygues L, Seifert M, Tilgen W, Reichrath J. 1,25-dihydroxyvitamin D(3) protects human keratinocytes against UV-B-induced damage: In vitro analysis of cell viability/proliferation, DNA-damage and -repair. Dermatoendocrinol 2009; 1:239-45; PMID:20592798; http://dx.doi.org/10.4161/derm.1.4.9705
10. Mason RS, Sequeira VB, Dixon KM, Gordon-Thomson C, Pobre K, Dilley A, et al. Photoprotection by 1alpha,25-dihydroxyvitamin D and analogs: further studies on mechanisms and implications for UV-damage. J Steroid Biochem Mol Biol 2010; 121:164-8; PMID:20399269; http://dx.doi.org/10.1016/j.jsbmb.2010.03.082
11. Dixon KM, Norman AW, Sequeira VB, Mohan R, Rybchyn MS, Reeve VE, et al. 1α,25$(OH)_2$-vitamin D and a nongenomic vitamin D analogue inhibit ultraviolet radiation-induced skin carcinogenesis. Cancer Prev Res (Phila) 2011; 4:1485-94; PMID:21733837; http://dx.doi.org/10.1158/1940-6207.CAPR-11-0165
12. Hanada K, Sawamura D, Nakano H, Hashimoto I. Possible role of 1,25-dihydroxyvitamin D_3-induced metallothionein in photoprotection against UVB injury in mouse skin and cultured rat keratinocytes. J Dermatol Sci 1995; 9:203-8; PMID:8664218; http://dx.doi.org/10.1016/0923-1811(94)00378-R
13. Okazaki T, Bell RM, Hannun YA. Sphingomyelin turnover induced by vitamin D_3 in HL-60 cells. Role in cell differentiation. J Biol Chem 1989; 264:19076-80; PMID:2808413
14. Manggau M, Kim DS, Ruwisch L, Vogler R, Korting HC, Schäfer-Korting M, et al. 1α,25-dihydroxyvitamin D_3 protects human keratinocytes from apoptosis by the formation of sphingosine-1-phosphate. J Invest Dermatol 2001; 117:1241-9; PMID:11710939; http://dx.doi.org/10.1046/j.0022-202x.2001.01496.x
15. Geilen CC, Bektas M, Wieder T, Kodelja V, Goerdt S, Orfanos CE. 1α,25-dihydroxyvitamin D_3 induces sphingomyelin hydrolysis in HaCaT cells via tumor necrosis factor α. J Biol Chem 1997; 272:8997-9001; PMID:9083023; http://dx.doi.org/10.1074/jbc.272.14.8997
16. Gniadecki R. Stimulation versus inhibition of keratinocyte growth by 1,25-Dihydroxyvitamin D_3: dependence on cell culture conditions. J Invest Dermatol 1996; 106:510-6; PMID:8648185; http://dx.doi.org/10.1111/1523-1747.ep12343866
17. Rass K. UV-damage and DNA-repair in basal and squamous cell carcinomas. In: Reichrath J, editor. Molecular mechanisms of basal cell and squamous cell carcinomas. Berlin: Springer; 2006. Austin: Landes Bioscience Medical Intelligence Unit
18. Gupta R, Dixon KM, Deo SS, Holliday CJ, Slater M, Halliday GM, et al. Photoprotection by 1,25 dihydroxyvitamin D3 is associated with an increase in p53 and a decrease in nitric oxide products. J Invest Dermatol 2007; 127:707-15; PMID:17170736; http://dx.doi.org/10.1038/sj.jid.5700597
19. Holowatz LA, Houghton BL, Wong BJ, Wilkins BW, Harding AW, Kenney WL, et al. Nitric oxide and attenuated reflex cutaneous vasodilation in aged skin. Am J Physiol Heart Circ Physiol 2003; 284:H1662-7; PMID:12505876
20. Su X, Paris M, Gi YJ, Tsai KY, Cho MS, Lin YL, et al. TAp63 prevents premature aging by promoting adult stem cell maintenance. Cell Stem Cell 2009; 5:64-75; PMID:19570515; http://dx.doi.org/10.1016/j.stem.2009.04.003
21. Paris M, Rouleau M, Pucéat M, Aberdam D. Regulation of skin aging and heart development by TAp63. Cell Death Differ 2012;19:186-93; PMID:22158419; http://dx.doi.org/10.1038/cdd.2011.181
22. Tuohimaa P, Keisala T, Minasyan A, Cachat J, Kalueff A. Vitamin D, nervous system and aging. Psychoneuroendocrinology 2009; 34(Suppl 1):S278-86; PMID:19660871; http://dx.doi.org/10.1016/j.psyneuen.2009.07.003
23. Keisala T, Minasyan A, Lou YR, Zou J, Kalueff AV, Pyykkö I, et al. Premature aging in vitamin D receptor mutant mice. J Steroid Biochem Mol Biol 2009; 115:91-7; PMID:19500727; http://dx.doi.org/10.1016/j.jsbmb.2009.03.007
24. Tuohimaa P. Vitamin D and aging. J Steroid Biochem Mol Biol 2009; 114:78-84; PMID:19444937; http://dx.doi.org/10.1016/j.jsbmb.2008.12.020
25. Haussler MR, Haussler CA, Whitfield GK, Hsieh JC, Thompson PD, Barthel TK, et al. The nuclear vitamin D receptor controls the expression of genes encoding factors which feed the "Fountain of Youth" to mediate healthful aging. J Steroid Biochem Mol Biol 2010; 121:88-97; PMID:20227497; http://dx.doi.org/10.1016/j.jsbmb.2010.03.019
26. Lin R, Nagai Y, Sladek R, Bastien Y, Ho J, Petrecca K, et al. Expression profiling in squamous carcinoma cells reveals pleiotropic effects of vitamin D3 analog EB1089 signaling on cell proliferation, differentiation, and immune system regulation. Mol Endocrinol 2002; 16:1243-56; PMID:12040012; http://dx.doi.org/10.1210/me.16.6.1243
27. Irminger-Finger I. Science of cancer and aging. J Clin Oncol 2007; 25:1844-51; PMID:17488982; http://dx.doi.org/10.1200/JCO.2007.10.8928
28. Bokov AF, Garg N, Ikeno Y, Thakur S, Musi N, DeFronzo RA, et al. Does reduced IGF-1R signaling in Igf1r$^{+/-}$ mice alter aging? PLoS One 2011; 6:e26891; PMID:22132081; http://dx.doi.org/10.1371/journal.pone.0026891
29. Su X, Paris M, Gi YJ, Tsai KY, Cho MS, Lin YL, et al. TAp63 prevents premature aging by promoting adult stem cell maintenance. Cell Stem Cell 2009; 5:64-75; PMID:19570515; http://dx.doi.org/10.1016/j.stem.2009.04.003