



Contents lists available at ScienceDirect

Seminars in Cancer Biology

journal homepage: www.elsevier.com/locate/semcancer

Review

An update on vitamin D signaling and cancer

Carsten Carlberg^{a,*}, Alberto Muñoz^b^a School of Medicine, Institute of Biomedicine, University of Eastern Finland, POB 1627, FIN-70211, Kuopio, Finland^b Instituto de Investigaciones Biomédicas 'Alberto Sols', Consejo Superior de Investigaciones Científicas–Universidad Autónoma de Madrid, CIBERONC and IdiPAZ, E-28029, Madrid, Spain

ARTICLE INFO

Keywords:

Vitamin D
 Calcitriol
 Vitamin D signaling
 VDR
 Vitamin D target genes
 Chromatin
 Epigenome
 Immune system
 Colon cancer
 Prostate cancer
 Breast cancer
 Hematological malignancies

ABSTRACT

A low vitamin D status is associated with an increased risk of various cancers, such as of colon, breast, prostate and hematological cells. The biologically most active vitamin D metabolite 1 α ,25-dihydroxyvitamin D₃ (1,25(OH)₂D₃) is a high affinity ligand of the transcription factor vitamin D receptor (VDR). 1,25(OH)₂D₃ induces via VDR changes to the epigenome of healthy and neoplastic cells and in this way influences their transcriptome. Ligand-activated VDR binds to more than 10,000 loci within the human genome and affects the transcription of some 1000 target genes in a large proportion of human tissues and cell types. From the evolutionary perspective, the prime role of vitamin D was probably the control of energy metabolism later shifting to modulate innate and adaptive immunity as well as to regulate calcium and bone homeostasis. Since rapidly growing immune and cancer cells both use the same pathways and genes for controlling their proliferation, differentiation and apoptosis, not surprisingly, vitamin D signaling changes these processes also in neoplastic cells. Thus, anti-cancer effects of vitamin D may derive from managing growth and differentiation in immunity. This review provides an update on the molecular basis of vitamin D signaling, *i.e.*, the effects of 1,25(OH)₂D₃ on the epigenome and transcriptome, and its relationship to cancer prevention and therapy.

1. Introduction

Cancer is the overarching term describing a multitude of very

heterogenous diseases that have in common displaying uncontrolled overgrowth of cells in any tissue of an individual [1]. The molecular basis of cancer is the accumulation of point mutations and copy number

Abbreviations: 1,25(OH)₂D₃, 1 α ,25-dihydroxyvitamin D₃, also called calcitriol; 25(OH)D₃, 25-hydroxyvitamin D₃, also called calcidiol; AML, acute myeloid leukemia; AMPK, adenosine monophosphate-activated protein kinase (official gene symbol: *PRKAA1*); APC, APC regulator of WNT signaling pathway; AXIN2, axin 2; BCL2, BCL2 apoptosis regulator; BRCA1, BRCA1 DNA repair associated; BRD7, bromodomain containing 7; CAF, cancer-associated fibroblast; CCND1, cyclin D1; CDH, cadherin; CDK, cyclin dependent kinase; CDKN, cyclin dependent kinase inhibitor; CEBPA, CCAAT/enhancer binding protein alpha; ChIP-seq, chromatin immunoprecipitation sequencing; CRC, colorectal cancer; CST5, cystatin D; CTCF, CCCTC-binding factor; CTNBN1, catenin beta 1; CXCL8, C-X-C motif chemokine ligand 8, also called IL8; CYP24A1, cytochrome P450 family 24 subfamily A member 1; DKK1, Dickkopf WNT signaling pathway inhibitor 1; EGF, epidermal growth factor; EGFR, epidermal growth factor receptor; ER, estrogen receptor (official gene symbols: *ESR1* and *ESR2*); FOS, Fos proto-oncogene, AP-1 transcription factor subunit; GABPA, GA binding protein transcription factor subunit alpha; HER2, human epidermal growth factor receptor 2 (official gene symbol: *ERBB2*); HOXA9, homeobox A9; ID1, inhibitor of DNA binding 1, HLH protein; IFNG, interferon gamma; IGF, insulin-like growth factor; IL, interleukin; JAK, Janus kinase; JUN, Jun proto-oncogene, AP-1 transcription factor subunit; KDM6B, lysine demethylase 6B; LGR5, leucine rich repeat containing G protein-coupled receptor 5; MAPK14, mitogen-activated protein kinase 14; MECOM, MDS1 and EVI1 complex locus; MEIS1, meis homeobox 1; miR, microRNA; MMP9, matrix metalloproteinase 9; MYC, MYC proto-oncogene, BHLH transcription factor; ncRNA, non-coding RNA; NF, normal fibroblast; PBMC, peripheral blood mononuclear cell; Pol II, RNA polymerase II; PR, progesterone receptor (official gene symbol: *PGR*); PU.1, purine-rich box 1, Spi-1 proto-oncogene (official gene symbol: *SPI1*); PTGER2, prostaglandin E receptor 2; PTGS2, prostaglandin-endoperoxide synthase 2, also called COX2; PTH, parathyroid hormone; RHOA, Ras homolog family member A; RNA-seq, RNA sequencing; RNF43, ring finger protein 43; ROCK1, Rho associated coiled-coil containing protein kinase 1; RPS6KA5, ribosomal protein S6 kinase A5, also called MSK1; RSPO2, R-spondin 2; RXR, retinoid X receptor; SERPINE1, serpin family E member 1, also called plasminogen activator inhibitor (PAI); SNAI, snail family transcriptional repressor; SPRY2, sprouty RTK signaling antagonist 2; STAT, signal transducers and activators of transcription; TAD, topologically associated domain; TCF7L2, transcription factor 7 like 2; TGFBR1, transforming growth factor beta receptor 1; T_H, T helper; TIMP1, TIMP metalloproteinase inhibitor 1; TLR, Toll-like receptor; TNBC, triple-negative breast cancer; TNF, tumor necrosis factor; TNC, tenascin C; T_{reg}, regulatory T; TSS, transcription start site; VDR, vitamin D receptor; VEGFA, vascular endothelial growth factor A; WNT3A, WNT family member 3A

* Corresponding author.

E-mail address: carsten.carlberg@uef.fi (C. Carlberg).<https://doi.org/10.1016/j.semcan.2020.05.018>

Received 26 March 2020; Received in revised form 21 May 2020; Accepted 27 May 2020

1044-579X/ © 2020 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

variations, such as amplification and deletions or big chromosomal alterations like translocations and aneuploidies, that enhance the activity of oncogenes and decrease that of tumor suppressor genes [2,3]. These genomic instabilities are modulated by epigenetic changes through direct actions of chromatin modifying enzymes as well as *via* indirect effects of transcription factors [4]. Both chromatin modifiers and transcription factors are often found at the endpoint of signal transduction cascades that are stimulated by various intra- and extracellular signals. Changes of the epigenome are triggered by signals of the cellular environment, such as nutrients, toxins and inflammation-related cytokines and chemokines [5]. Thus, epigenetic changes can have both detrimental as well as beneficial effects on cancer onset and progression.

The worldwide increase in life expectancy raises the rates of cancer morbidity and mortality, with some 18 million new cancer cases and nearly 10 million cancer deaths in 2018 [6]. The costly treatment of the disease, such as surgery, radiation therapy and chemotherapy, is a financial burden for the healthcare systems of developed countries and is even not easily accessible to the majority of the population in developing countries [7]. Thus, there is urgent need for anti-cancer options that combine preventive with therapeutic potentials, ideally at low cost.

In this context vitamin D₃ (also called cholecalciferol) has gained significant attention as an inexpensive and readily accessible natural compound [8]. The main source of this seco-steroid is its non-enzymatic production in human skin from UV-B exposed 7-dehydrocholesterol, which is an abundant direct cholesterol precursor (Fig. 1A) [9]. Circulating vitamin D₃ from endogenous production as well as from dietary uptake is converted in the liver to 25-hydroxyvitamin D₃ (25(OH)D₃, also called calcidiol). The serum concentration of this most stable vitamin D metabolite is used as biomarker for the vitamin D status of a person [10]. The natural way of producing vitamin D₃ *via* UV-B exposure of the skin should be used with precaution, since excessive sun bathing leads to sunburn and may cause different types of skin cancer. Unfortunately, only a limited number of foods, such as the fatty fishes salmon, tuna and mackerel, contain substantial amounts of vitamin D₃. Moreover, only in a few countries foods, such as milk, dairy products, orange juice and margarines, are regularly fortified with vitamin D₂ (also called ergocalciferol) or vitamin D₃ [11]. This makes direct supplementation with vitamin D₃ (800–4000 IU, *i.e.*, 20–100 µg/day) an alternative strategy for optimizing the vitamin D status to 25(OH)D₃ serum levels of 75–150 nM (*i.e.*, 30–60 ng/mL) [12].

The hydroxylation of 25(OH)D₃ at carbon 1, taking place primarily in the kidneys and also in several types of epithelial and immune cells, leads to 1,25(OH)₂D₃ (also called calcitriol, Fig. 1A), which is the high-affinity ligand of the transcription factor VDR [13]. In this way, in the nucleus vitamin D has a direct effect on gene regulation and *via* the actions of VDR it also affects the epigenome (Fig. 1B) [14]. Moreover, in a variable cell-type and -context a proportion of VDR molecules locate in the cytosol, where they mediate ligand-dependent, rapid modulatory effects on signaling pathways affecting enzymes, kinases, phosphatases and ion channels. These effects do not require changes in gene transcription and are called non-genomic actions [15]. Thus, vitamin D₃ and its metabolites may be ideal compounds for modulating intracellular pathways with impact on cellular growth, differentiation and apoptosis.

This review will provide an update of excellent previous surveys [16–18] on the molecular and cellular basis of vitamin D signaling and its relationship to cancer prevention and therapy.

2. Linking vitamin D with cancer prevention

Already 40 years ago, an epidemiological study suggested that vitamin D may be protective against colorectal cancer (CRC), since increased sun (UV-B) exposure as well as a life at lower latitudes (both causing higher vitamin D₃ formation) leads to a lower incidence for this type of cancer [19]. Interestingly, at about the same time 1,25(OH)₂D₃

was found to have *in vitro* an anti-proliferative effect on melanoma cells [20]. In general, a low vitamin D status seems to be associated with a higher cancer incidence [21]. A number of vitamin D intervention trials with different types of cancer, but not all, confirmed this observation and most convincing data were presented for CRC [22–24]. Moreover, there are many *in vitro* studies and a few *in vivo* data indicating that vitamin D is also effective against breast and prostate cancer as well as leukemia and lymphoma. A final answer concerning the impact of vitamin D on cancer prevention was expected from randomized control trials.

The large randomized control trial VITAL [25] had enrolled 25,871 participants without a history of cancer and used 2000 IU (50 µg) vitamin D₃ per day for primary prevention of cancer within a period of 5 years. Although the primary analysis of that study did not report any significant reduction in the risk of cancer mortality, a secondary analysis suggested a benefit of vitamin D₃ after exclusion of early follow-up data and for subgroups of individuals in cancer incidence and/or mortality [25,26]. Similarly, a meta-analysis [27] of three other randomized control trials [28–30], each of them having a null result, found that vitamin D₃ supplementation leads to a significantly lower total cancer mortality. In this context, the concept of a personalized vitamin D response index [31] may be taken into account. As shown with Finnish cohorts [32,33] about 25 % of the population seem to be low responders to vitamin D supplementation, *i.e.*, these persons need higher daily doses of vitamin D₃, in order to reach the full clinical benefit. So far, participants of randomized control trials have not been stratified for low, mid and high vitamin D responders. Moreover, many study subjects were recruited with a rather high vitamin D status, *i.e.*, they may have been in the range of vitamin D sufficiency and did not need further supplementation.

In summary, a stratification of the participants, a better design including the analysis of health outcomes in relation to changes in individual serum 25(OH)D₃ values and an adequate duration of the study/follow-up as well as the type of statistical analysis majorly influence the final conclusion taken from randomized control trials on vitamin D [34].

3. Vitamin D and its receptor

The 48 nuclear receptors encoded by the human genome form an unusual superfamily of transcription factors, since the majority of these proteins can be activated by small lipophilic molecules in the range of the molecular mass and volume of cholesterol [35]. Prominent members of the superfamily are the endocrine receptors for estrogen, progesterone and cortisol (estrogen receptors (ERs), progesterone receptor (PR) and glucocorticoid receptor) as well as the adopted orphan receptors for fatty acids and oxysterols (peroxisome proliferator-activated receptors and liver X receptors) [36]. Nuclear receptors are characterized by a structurally conserved ligand-binding domain [37]. In case of VDR, some 40 mostly non-polar amino acids within this domain form a ligand-binding pocket that fixes 1,25(OH)₂D₃ or its synthetic analogs with high specificity [38]. Accordingly, VDR is the only protein that binds at sub-nanomolar concentrations (K_D 0.1 nM) the biologically most active form of vitamin D₃ [39], *i.e.*, VDR is the exclusive mediator of the effects of physiological concentrations of 1,25(OH)₂D₃.

The high-affinity 1,25(OH)₂D₃-binding VDR protein evolved already some 550 million years ago in a boneless vertebrate [40]. The initial function of VDR was most likely the regulation of energy metabolism [41]. The fact that the innate immune system and the developing adaptive immunity require substantial amounts of energy [42] seem to have served as a starting point how vitamin D and its receptor got *via* the control of immunometabolism a modulatory impact on immunity [43]. Since immune cells are the most rapidly growing cells of the body, the functions of vitamin D also extended to the control of cellular proliferation, differentiation and apoptosis [44]. Some 400 million years ago some fish species left the calcium-rich ocean and

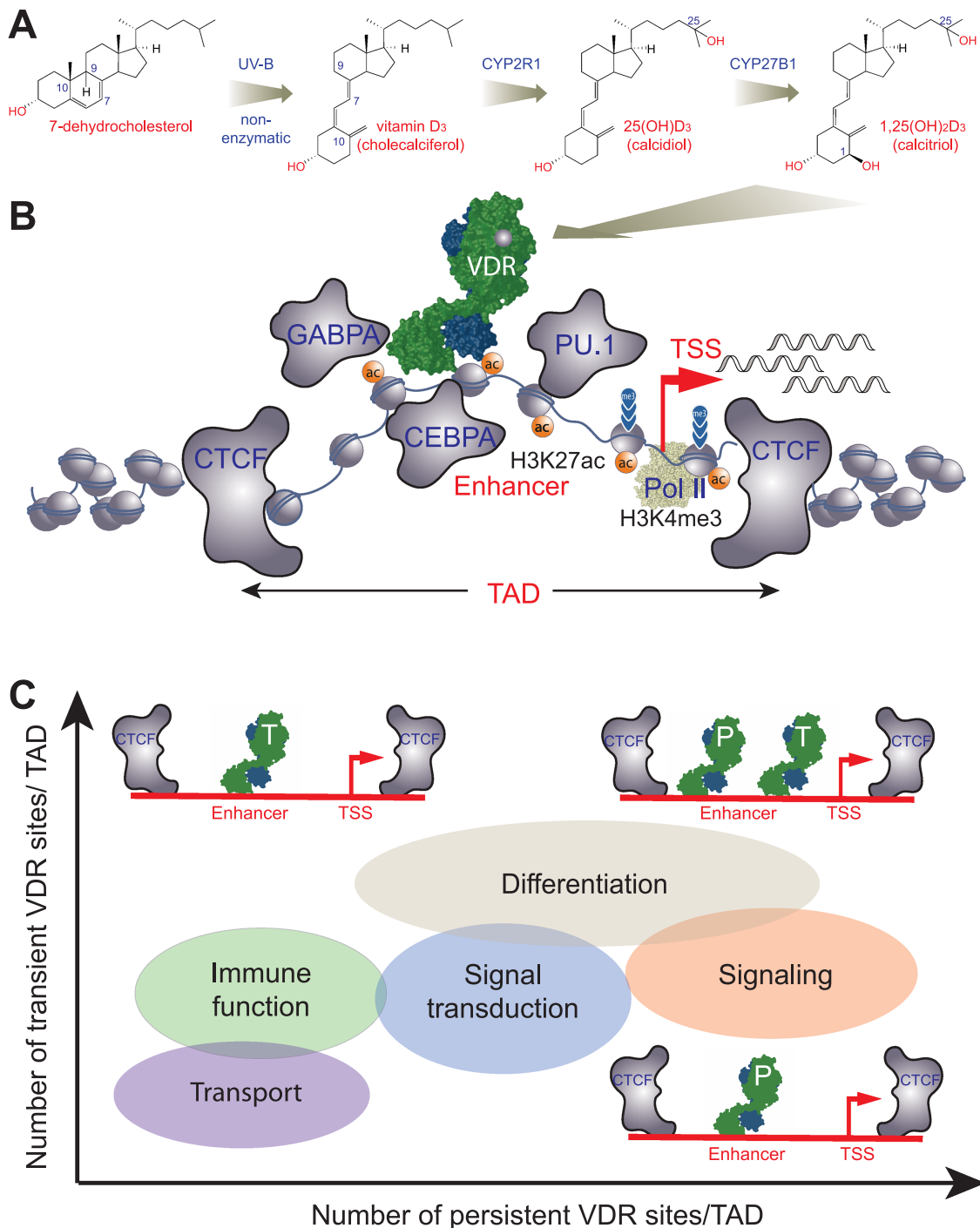


Fig. 1. Vitamin D signaling. Production of vitamin D₃ and its metabolites 25(OH)D₃ and 1,25(OH)₂D₃ (A). VDR (green) binds accessible genomic DNA in complex with a partner protein (RXR or others, blue) (B). VDR's DNA binding is supported by the pioneer factors PU.1, CEBPA and/or GABPA. The genomic region that can be influenced by 1,25(OH)₂D₃ (via binding to VDR) is restricted by CTCF proteins defining left and right TAD borders. Schematic representation of a Voronoi tessellation [55] displaying five TAD classes of the most prominently enriched biological processes (C). The most relevant attributes are the number of persistent and transient VDR sites and were chosen for the x and y axis, respectively.

populated the calcium-poor land, where they were exposed to gravitation making a more stable skeleton essential [45]. At that time vitamin D and VDR gained the additional role of regulating calcium homeostasis, which is indispensable for proper bone formation. In this physiological function vitamin D obtained key importance [46], *i.e.*, in contrast to its previous tasks no other regulatory molecules are able to replace vitamin D. This explains why the prime phenotype of vitamin D deficiency is bone malformation, such as occurring in rickets [47]. Nevertheless, the rather ubiquitous expression of the *VDR* gene in more

than half of the 400 human tissues and cell types (www.proteinatlas.org/ENSG00000111424-VDR/tissue) indicates that vitamin D and its receptor have a wider physiological role than the regulation of calcium homeostasis [48].

The VDR cistrome, *i.e.*, the genome-wide binding pattern of the transcription factor, is determined via the next-generation sequencing method chromatin immunoprecipitation sequencing (ChIP-seq) [49]. This cistrome had been obtained in immortalized primary human cell types, such as B lymphocytes (GM10855, GM10861) and cells from 30

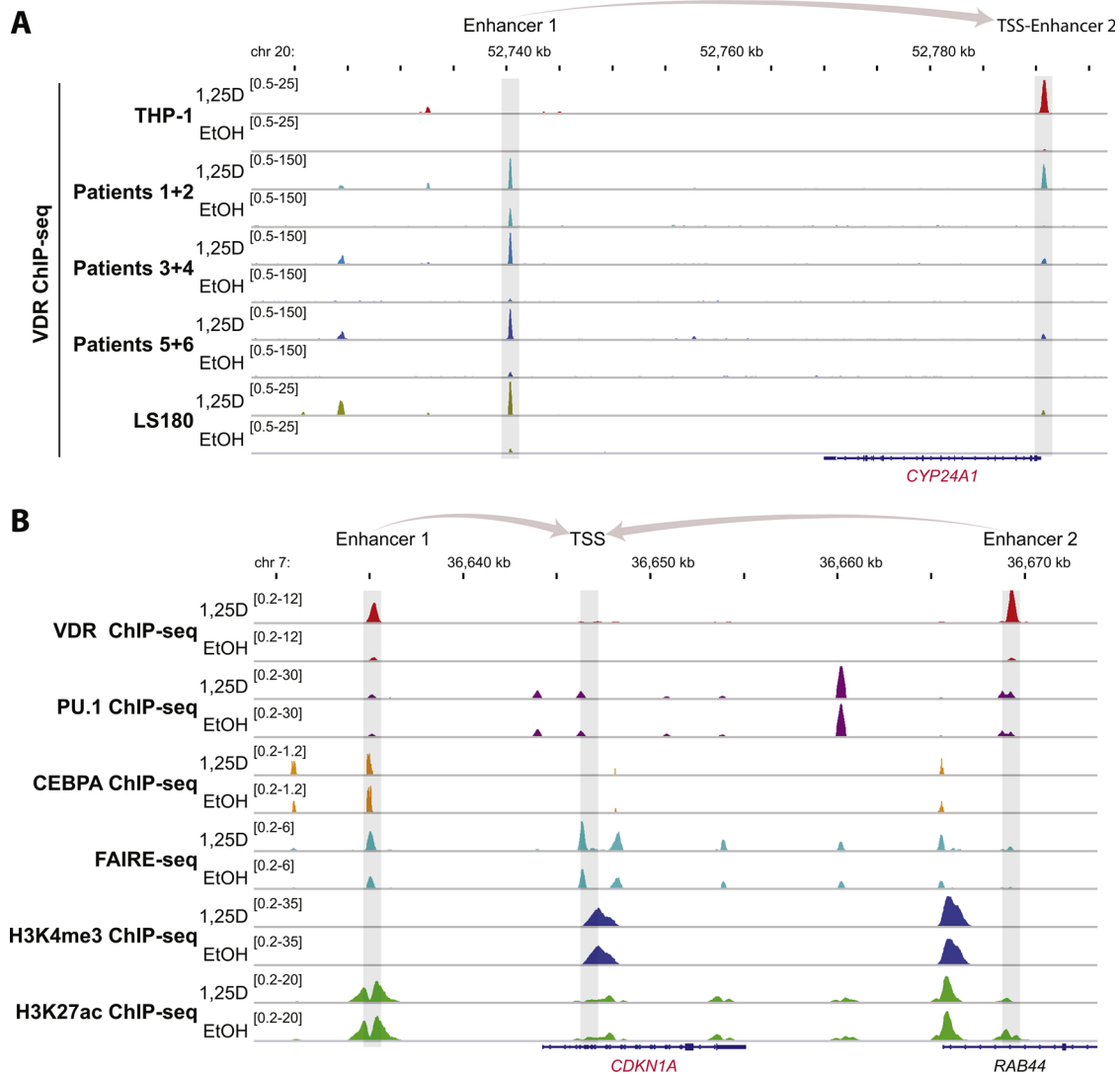


Fig. 2. VDR binding and epigenomic profiles in the region of vitamin D target genes. The IGV browser [201] was used to display the epigenomic profiles at enhancer and TSS regions of the vitamin D target genes *CYP24A1* (A) and *CDKN1A* (B). VDR ChIP-seq data are derived from single experiments performed with organoid cultures of three pairs of CRC patients [57] or cultured LS180 cells [56]. For THP-1 cells the peak tracks display merged data from three biological repeats of ChIP-seq experiments with antibodies against VDR [55], PU.1 [84], CEBPA [85], H3K4me3 [80] and H3K27ac [80] as well as FAIRE-seq data [79] treated for 24 h with 1,25(OH)₂D₃ (1,25D) or vehicle (EtOH). The gene structures are shown in blue and vitamin D target genes are indicated in red.

other HapMap individuals) [50,51], hepatic stellate cells (LX2) [52] and prostate epithelial cells (RWPE1) [53], as well as in cell lines derived from acute monocytic leukemia (AML) of a 1-year-old male (THP-1) [54,55] and CRC of a 58-year-old female (LS180) [56]. In addition, VDR ChIP-seq had been performed with epithelial stem cell-derived organoids of normal tissue of CRC patients [57] as well as with primary normal fibroblasts (NFs) of healthy donors [58] and kidney cortex of human cadavers [59]. From all investigated cellular models, leukemia cells (THP-1) have been studied most extensively for the molecular mechanisms of vitamin D signaling [60]. VDR binding sites drastically up-regulating the gene *CYP24A1* (cytochrome P450 family 24 sub-family A member 1) in THP-1 cells, normal organoids of three different pairs of CRC patients and LS180 cells are displayed as a representative example (Fig. 2A). *CYP24A1* is the key vitamin D catabolizing enzyme and regulates the levels of 25(OH)D₃ and 1,25(OH)₂D₃ [61], the expression of which is mostly negatively associated with cancer prognosis [62].

Depending on the cell type, the VDR cistrome comprises many thousand VDR binding sites spreading tissue-specifically over the human genome [63]. This is the most likely explanation why cell types

differ majorly in their set of vitamin D target genes [64–66]. However, one common observation in all cell types is that a stimulation with 1,25(OH)₂D₃ leads to a 2- to 10-fold increase in genome-wide VDR binding events [63]. In an average normal or malignant human cell, the VDR cistrome is formed by some 10,000 genomic loci. This is far more than the average number of vitamin D target genes, which is in the order of 200–1000 genes per cell type [57,64–67], i.e., not all VDR binding sites seem to have an impact on gene regulation. However, there are a few hundred VDR loci, on which after ligand stimulation receptor occupancy changes significantly over time while they are always bound to their loci [55]. These persistent VDR binding sites serve as primary contact points for the communication of vitamin D with the human genome, i.e., they act as “hotspots” of vitamin D signaling. In contrast, other VDR sites are only transiently occupied or used exclusively in later steps of the gene activation cascade.

Taken together, vitamin D-triggered binding of VDR to the human genome is the most pronounced and well-understood epigenome-wide effect of 1,25(OH)₂D₃ [14].

4. Epigenetic basis of vitamin D signaling

Chromatin is a complex of genomic DNA and nucleosomes, which are formed by histone proteins [68]. The epigenome of a cell represents the genome-wide information included in covalent and structural modifications of its chromatin [69]. The epigenome controls the access of transcription factors to their genomic binding sites [70] *via* changes in i) cytosine methylation, in particular at the sites of CpG islands, ii) more than 100 different types of post-translational modifications of histone proteins and iii) the 3-dimensional (3D) organization of the nucleus, such as topologically associated domains (TADs) [71]. For example, well-known markers for active chromatin are acetylated histone H3 proteins at position lysine 27 (H3K27ac), while active transcription start site (TSS) regions are marked by H3K4me3 modifications [72].

The main regulatory regions of a gene are its TSS as well as the binding sites for transcription factors, referred as enhancers, which are found in a Gaussian-type distribution both up- and down-stream of the TSS (Fig. 1B) [73]. The expression of a vitamin D target gene is critically dependent on whether the TSS and at least one VDR-binding enhancer are located within accessible chromatin [74]. However, more than 90 % of the genomic DNA of a differentiated cell is not accessible, *i.e.*, chromatin largely acts as an intrinsic repressor of gene expression [75,76]. Thus, the so-called “epigenetic landscape” of a differentiated cell type is restricted to some 100–200,000 genomic loci, most of which represent TSS and enhancer regions [73]. Interestingly, the transformation of a normal cell into a cancer cell includes multiple changes in this epigenetic landscape [77]. This de-differentiation process results in an increased number of accessible chromatin regions [78]. Importantly, the epigenome can be modulated by environmental signals, such as 1,25(OH)₂D₃, *i.e.*, in contrast to the genome the epigenome is dynamic. This implies the potential that vitamin D can re-arrange the epigenome of a tumor cell or its microenvironment [17].

The stimulation of leukemia cells (THP-1) with 1,25(OH)₂D₃ induces significant changes in the accessibility of their epigenome affecting nearly 9000 of 62,000 open chromatin loci [79]. Similarly, in the same cell line 550 of 22,998 genomic regions with H3K4me3 modifications and 2473 of 45,578 regions with H3K27ac marks respond significantly to a stimulation with 1,25(OH)₂D₃ [80]. Thus, vitamin D is able to modulate the activity of the epigenome of a cancer cell at more than 500 promoter regions and some 2500 enhancer regions. VDR binding was detected at some 25 % of these chromatin regions, while the remaining 1,25(OH)₂D₃-triggered sites of the epigenome seem to represent secondary effects of the nuclear hormone. VDR interferes with chromatin modifying proteins, such as KDM6B (lysine demethylase 6B), and the chromatin remodeler BRD7 (bromodomain containing 7). This happens *via* direct and indirect interactions of VDR with these proteins, such as being part of the same large protein complex in the nucleus [81,82] or the regulation of the genes encoding them [83], respectively.

Like most other regular (“settler”) transcription factors, VDR functionally interferes with “pioneer” transcription factors, such as PU.1 (purine-rich box 1) [84], CEBPA (CCAAT/enhancer binding protein alpha) [85] and GABPA (GA binding protein transcription factor subunit alpha) [86] (Fig. 1B). Pioneer factors help regular transcription factors to access their genomic binding sites, *i.e.*, in general they amplify the action of settler transcription factors [87]. For example, PU.1 and VDR work together in the process of monocyte and granulocyte differentiation during hematopoiesis [88]. In THP-1 cells on 2/3 of all VDR binding sites also PU.1 is found [84]. Thus, on the genome-wide level PU.1 shows a far higher rate of co-location with VDR as its traditional DNA-binding partner retinoid X receptor (RXR) [63].

Interestingly, at a subset of some 5% of all PU.1 sites 1,25(OH)₂D₃ significantly supports the DNA binding of the pioneer factor, *i.e.*, VDR can also act as a pioneer for PU.1 [84]. A similar functional interference of vitamin D signaling was observed with the chromatin

organizing protein CTCF (CCCTC-binding factor). In THP-1 cells, 1321 of the in total 23,658 CTCF binding sites are significantly affected by a stimulation with 1,25(OH)₂D₃ [79,89]. CTCF is one of the key proteins organizing the 3D structure of chromatin *via* binding to TAD anchors [90]. The anchors of these chromatin loops act as insulators towards neighboring TADs and are often conserved between tissues and species [91,92]. Vitamin D-sensitive CTCF sites affect the activity of some 600 TADs and the vitamin D target genes included in them (Fig. 1B). Since the human genome is segregated into approximately 3000 TADs [93], some 20 % of all TADs seem to be sensitive to vitamin D.

In summary, vitamin D influences the epigenome not only *via* changes of the chromatin accessibility status affecting VDR and pioneer factor binding, but also on the level of 3D chromatin structure.

5. The vitamin D transcriptome and cancer

Primary vitamin D target genes are modulated in their expression, *i.e.*, in most cases they are up-regulated, when they co-locate on the same TAD with an enhancer region carrying a persistent and/or transient VDR binding site (Fig. 1C) [55]. We define primary vitamin D target as those genes that are significantly up- or down-regulated within 4 h after stimulation with 1,25(OH)₂D₃ [79]. VDR-activated enhancers activate *via* DNA looping RNA polymerase II (Pol II) on TSS regions leading to a stimulation mRNA production. This defines for most VDR sites and their target genes a chromosomal environment determining which gene is controlled by which receptor locus in its vicinity [94]. Transient sites, *i.e.*, VDR loci that are occupied only at certain time points after ligand stimulation, modulate the vitamin D responsiveness of the epigenome, *i.e.*, they support the actions of VDR molecules binding at persistent sites. Interestingly, the most critical attribute for the functional distinction of vitamin D-modulated TADs is the relative number of persistent and transient VDR sites [55]. For example, vitamin D target genes that are critical for immune function responding in an “on/off” modus and are primarily up-regulated by transient VDR loci (Fig. 1C) [94]. Persistent and transient VDR loci build up a specific local epigenomic environment that influences chromatin accessibility as well as histone modifications at TSS and enhancer regions. Thus, vitamin D-triggered changes of the epigenome and its consequences on the transcriptome are secondary effects of the activity of persistent and transient VDR sites acting on primary vitamin D target genes.

The chromatin model of vitamin D signaling (Fig. 1B) describes vitamin D-triggered changes of the association of VDR and pioneer factors with their genomic sites affecting chromatin accessibility [14,60]. This results in a significant modulation of the expression of one or more primary vitamin D target genes located within the same TAD [95]. This implies that epigenetic changes occurring during the process of tumorigenesis influence the response of vitamin D target genes. However, this mechanism also bears the potential that a sufficient vitamin D status of a cancer patient may lead to epigenetic changes within tumor cells that affect critical target genes, such as the up-regulation of the cell cycle inhibitor *CDKN1A* (cyclin dependent kinase inhibitor 1A) [96,97], resulting in growth arrest (Fig. 2B). Thus, vitamin D-triggered changes of the epigenome in the genomic region of the *CDKN1A* gene keep the gene actively transcribed and allow its encoded protein to act as inhibitor of the cell cycle *via* binding to cyclin-cyclin-dependent kinase (CDK) complexes.

Transcriptome-wide studies using microarrays and RNA sequencing (RNA-seq) in various cellular systems (including cell lines representing prostate, breast, ovarian, colorectal, squamous cell carcinoma and leukemia [66]) identified a large set of primary and secondary vitamin D target genes. The latter are genes that are not directly regulated by VDR but are up- or down-regulated *via* transcription factors, chromatin modifiers or non-coding RNAs (ncRNAs) that are encoded by primary vitamin D target genes. Some of these are regulators of the cell cycle [98–100]. Common cellular processes targeted by vitamin D are cell cycle progression, apoptosis, cellular adhesion, oxidative stress,

Table 1

1,25(OH)₂D₃ target genes in human colon and breast cancer cells. List of key representative genes regulated by 1,25(OH)₂D₃ in human colorectal and breast cancer or stromal cells indicating the process and signaling pathway they are involved in.

Gene	Process/Pathway	Cell type	Cancer type	Refs.
<i>MYC, JUN, JUNB, JUND, FOS...</i>	Proliferation/transcription	Carcinoma cells	Colorectal	[56,98,100,145]
<i>CCND1, CDKN1A, CDKN1B, GOS2...</i>	Proliferation/cell cycle control	Carcinoma cells	Colorectal	[56,98]
<i>EGFR, SPRY2, AREG</i>	Proliferation/growth factor signaling	Carcinoma cells	Colorectal	[100,147,148,149]
<i>CDH1, OCLN, CLD2, TJP1, CASR, FLNA...</i>	Differentiation/cell adhesion	Carcinoma cells	Colorectal	[99,141]
<i>KDM6B</i> , other histone demethylases	Epigenetic regulation	Carcinoma cells	Colorectal	[83,152]
<i>BAK, BAG, BIRC5, BAX, GOS2, IGF1BP3</i>	Apoptosis	Carcinoma cells	Colorectal	[98,138]
<i>HIF1A, VEGF, DKK4...</i>	Migration, angiogenesis, invasiveness	Carcinoma cells	Colorectal	[98,150,151]
<i>CST5, DKK1</i>	Proliferation, differentiation, migration...	Carcinoma cells	Colorectal	[142,153,155]
<i>CYP3A4 SULT2A1, ABCG1...</i>	Detoxification, metabolism	Carcinoma cells	Colorectal	[98,138]
Protease, protease inhibitors	Pleiotropic effects/protein half-life	Carcinoma cells	Colorectal	[98,155]
<i>miR22</i>	Proliferation, migration	Carcinoma cells	Colorectal	[156]
<i>RELA, NFKB1A</i>	Immunomodulation/transcription	Carcinoma cells, immune cells	Colorectal	[108]
<i>IL1B, IL6, IL6, IL8, IL10, IL17, IL23</i>	Immunomodulation/intercellular communication, cytokines	Carcinoma cells, immune cells	Colorectal	[108]
<i>CCL2, CCL11, CCL13, CYT11</i>	Intercellular communication/chemokines	CAFs	Colorectal	[67]
<i>NID2...</i>	Extracellular matrix	CAFs	Colorectal	[67]
<i>TIMP3, S100A4, CD82, SEMA3B</i>	Migration, invasiveness, metastasis	CAFs	Colorectal	[67]
<i>DKK4, TFF2, JSRP1, S100 P, TNS4, BCAS1, CA2...</i>	Proliferation, invasiveness	Cancer stem cell-derived organoids	Colorectal	[57]
<i>MYC, CCND1, CDK2, CDK4, CDKN1A...</i>	Proliferation/cell cycle control	Carcinoma cells	Breast	[177]
<i>CDH1, CDH2, CDH3</i>	Differentiation/cell adhesion	Carcinoma cells	Breast	[175]
<i>TIMP1, MMP9, TNC, ITGA6, ITGB4, VEGFA, ID1</i>	Migration, angiogenesis, invasiveness	Carcinoma cells	Breast	[175,176,177]
<i>BCL2</i> family	Apoptosis	Carcinoma cells	Breast	[172,173,174]
<i>ESR1, CYP19A1</i>	Proliferation/estrogen signaling	Carcinoma cells, stromal adipocytes	Breast	[178,179]
<i>PTGS2, PTGER2</i>	Proliferation/prostaglandin signaling	Carcinoma cells, stromal adipocytes	Breast	[178,179]

immune function and steroid metabolism. The most comprehensive description of the vitamin D-modulated transcriptome, as determined by RNA-seq [101], was performed with leukemia cells (THP-1), which were stimulated for 2.5, 4 and 24 h with 10 nM 1,25(OH)₂D₃ [79]. Statistics for differential expression initially indicated 1284 vitamin D target genes [79], while a re-analysis of this dataset reduced the number of genes to 587 [55]. A bit more than half (311) of these genes are primary targets of vitamin D. Gene ontology analysis indicated that immune functions, such neutrophil signaling and inflammatory responses, are the most significant process regulated by these primary vitamin D target genes [95].

Transcriptomic studies in human CRC have been performed in immortal carcinoma cell lines, in primary patient-derived NFs, in cancer-associated fibroblasts (CAFs) and in organoids generated by normal and cancer stem cells (Table 1). The first microarray analysis showed a regulation of hundreds of genes after 4 and 48 h of 1,25(OH)₂D₃ treatment (10 nM) in SW480-ADH cells and a far lower number of genes in LS174 T cells [98]. Most target genes were up-regulated and their encoded proteins were preferentially involved in transcription, cell adhesion, DNA synthesis, apoptosis, redox status and intracellular signaling. In another microarray study performed in Caco-2 adenocarcinoma cells 12 genes (including *CYP24A1* and others potentially involved in inhibition of cell proliferation) were found to be regulated upon 24 h treatment with 10 nM 1,25(OH)₂D₃ [100]. A later microarray study in LS180 cells with a 24 h treatment (10 nM) identified further 1,25(OH)₂D₃ target genes responsible for vitamin D catabolism, calcium and phosphate uptake, secondary bile acid metabolism and xenobiotic degradation and control of cell proliferation, such as *MYC* (*MYC* proto-oncogene, BHLH transcription factor) and *FOS* (*Fos* proto-oncogene, AP-1 transcription factor subunit) [56]. As confirmed later by ChIP-seq analysis (3 h, 10 nM 1,25(OH)₂D₃) also in other cell systems, the majority of potential regulatory VDR binding sites are located far from the TSSs or in introns of their target genes.

When considering the putative relevance of these transcriptomic studies, it is convenient to remind that cell lines used have complex and heterogeneous mutational landscapes following long-term culture. Moreover, in some cases these cell lines, such as Caco-2 cells, which are

of colon origin but shows the phenotype of small intestinal epithelium, do not properly model the correct type of cancer.

A strong regulatory effect of 1,25(OH)₂D₃ has been found in human colon stromal fibroblasts in a microarray study (48 h, 10 nM 1,25(OH)₂D₃) highlighting 958 genes (47 % up-regulated, 53 % down-regulated) in NFs and even 1489 genes (35 % up-regulated, 65 % down-regulated) in CAFs [67]. These gene lists partially overlap and most of the genes are involved in cell adhesion and migration, extracellular matrix organization, blood vessel development, inflammatory response and cell communication. In an RNA-seq study in the immortal CCD-18Co human colon fibroblast cell line, 1,25(OH)₂D₃ (24 h, 10 nM) and WNT3A (WNT family member 3A) showed additive, partially overlapping effects on the transcriptome. Curiously, both agents inhibit the proliferation and migration capacities of CCD-18Co cells, while 1,25(OH)₂D₃ reduces but WNT3A increases the ability to contract collagen gels. The latter is a surrogate marker of the capacity to alter the extracellular matrix, which is a hallmark of fibroblast activation. These effects were reproduced in patient-derived NFs and CAFs as well as in fibroblastic cell lines of several origins suggesting that 1,25(OH)₂D₃ and WNT3A regulate the gene expression and phenotype of human colon fibroblasts [102].

In patient-derived colon tumor organoids, a 96 h treatment with 10 nM 1,25(OH)₂D₃ changes the RNA level of 1182 genes (643 up-regulated, 539 down-regulated), while in matched (same patient) normal organoids generated from healthy colon tissue the number of target genes was high as 2107 (943 up-regulated, 1164 down-regulated) [57]. Only 19.3 % of the genes in these lists overlap, which indicates that 1,25(OH)₂D₃ regulates distinctly genes, e.g., related to cell stemness and differentiation, in the two types of organoids. In these and other transcriptomic studies with 1,25(OH)₂D₃ over longer time periods, approximately half of the target genes are down-regulated, i.e., the level of their RNA transcripts are diminished by 1,25(OH)₂D₃. Gene repression by ligand-modulated nuclear receptors, such as VDR, is primarily an indirect and/or post-transcriptional effect mediated by the products of primary target genes, such as transcription factors, chromatin modifiers and ncRNAs, through protein-protein interactions, signaling interference or microRNAs (miRs). In contrast, in a process referred to

as transrepression ligand-induced VDR directly represses primary vitamin D target genes, such as *PTH* (parathyroid hormone) in the parathyroid gland [103] and *CYP27B1* in the kidneys [104].

Taken together, $1,25(\text{OH})_2\text{D}_3$ significantly changes the transcriptome of healthy and malignant cell types at 1000–2000 genomic loci. Longer VDR ligand treatments lead to a higher percentage of secondary vitamin D target genes. However, a weakness of these studies is the heterogeneity of the cell types, their treatment protocols, such as number of replicates, duration and doses of $1,25(\text{OH})_2\text{D}_3$, and the statistical analyses making it difficult to translate their results to the identification of target genes.

6. Impact of the immune system on the anti-cancer role of vitamin D

There is large consensus that the modulation of the immune system is the most important extra-skeletal function of vitamin D [105,106]. Vitamin D stimulates the innate immune system in fighting more efficiently against bacterial infections, such as tuberculosis [105], while it prevents overreactions of the adaptive immune system that may cause autoimmune diseases, such as multiple sclerosis [107,108]. On the basis of transcriptome-wide datasets from THP-1 cells (monocytes) and human peripheral blood mononuclear cells (PBMCs, a mixture of lymphocytes and monocytes) treated *in vitro* with $1,25(\text{OH})_2\text{D}_3$ as well as from PBMCs of individuals supplemented with a vitamin D₃ bolus three groups of immune-related vitamin D target genes had been identified that represent the functions acute response to infection, infection in general and autoimmunity [109]. Interestingly, the vitamin D target genes can be differentiated in their epigenomic profile, such as the types of VDR-driven enhancers, as well as *via* the dynamics of their mRNA production.

In general, vitamin D acts as an inducer of innate immunity, such as *via* the prominent up-regulation of the secreted anti-microbial peptide cathelicidin or plasma membrane-anchored glycoprotein CD14 [110]. CD14 functions as a co-receptor for the pattern recognition receptors Toll-like receptors (TLRs) [111] and delivers the pathogen-associated molecular pattern lipopolysaccharide to TLR4. Thus, the early response of monocytes and macrophages to vitamin D stimulation is a pro-inflammatory action [112]. In a later step vitamin D often shifts the polarization of macrophages from the pro-inflammatory, anti-tumor stage M1 to the immunosuppressive, pro-tumor M2 stage [113]. However, please note that the stages M1 and M2 are considered the extremes of a wide spectrum of plasticity of macrophages that is sensitive to epigenetic programming by vitamin D and its receptor VDR [60,114]. Thus, the anti-inflammatory and immunosuppressive functions of vitamin D are paired in certain cases with a pro-tumor effect.

Vitamin D deficiency is associated with Crohn's disease and ulcerative colitis, which are the two predominant pathophysiological manifestations of inflammatory bowel disease [115,116]. The rates of inflammatory bowel disease are probably increasing due to modern lifestyles that affect the function of the gut microbiome *via* high levels of saturated fat and sugar in diet as well as the use of antibiotics [117]. Vitamin D is important for regulating the immunity of gut mucosa *via* the modulation of innate immune barrier function, gut epithelial integrity and the development and function of T cells [118,119]. Thus, vitamin D can prevent the onset of inflammatory bowel disease through the stabilization of microbiota homeostasis as well as ameliorates disease progression *via* anti-inflammatory immune responses. Interestingly, in persons with increase susceptibility for inflammatory bowel disease vitamin D deficiency is a contributing factor to the disease [120].

Knockout mice for *CYP27B1* [121] as well as for *VDR* [122] show increased severity of experimentally-induced colitis that mimics inflammatory bowel disease, *i.e.*, the inability to synthesize or recognize $1,25(\text{OH})_2\text{D}_3$ increases the severity of inflammatory bowel disease. Moreover, a treatment with $1,25(\text{OH})_2\text{D}_3$ improves the conditions of

experimental colitis in murine models [115,123]. Accordingly, a low vitamin D status is a significant risk factor for the onset of CRC in individuals with inflammatory bowel disease [124].

Vitamin D mostly functions as a repressor of adaptive immunity, as it down-regulates the number of T_H (T helper) 1 cells and increase that of T_H2 cells and T_{reg} (T regulatory) cells. However, the majority of these observations were made in experimental settings in which the cells were overstimulated. Thus, vitamin D may have a late role accelerating the resolution of inflammation following an early role in its initial activation [108,125–127]. Interestingly, a human intervention trial indicated that in the context of Western diet vitamin D₃ supplementation increases the expression of inflammatory genes in colon cells, while additional supplementation with calcium reverses this effect [128]. This may explain how a sufficient vitamin D status combined with high dietary calcium intake is linked to lower CRC risk.

Vitamin D actions on the immune system involve the growth, differentiation, activation/deactivation and eventually apoptosis of different types of immune cells, such as monocytes, dendritic cells and different types of T cells [129]. Importantly, immune and cancer cells use the same signal transduction pathways and genes for pushing their growth [130]. Therefore, it is possible that the anti-proliferative and differentiation- and apoptosis-inducing potential of vitamin D on cancer cells derives from pathways that were initially evolved for the growth control of immune cells, such as the up-regulation of the *CDKN1A* gene [131]. Moreover, these cell types are also found in the microenvironment of tumors, *i.e.*, some aspects of the anti-cancer effects of vitamin D could be explained by a modulation of the immune component of the microenvironment, which may be detrimental for cancer cells [132,133].

Tumor cells present at their plasma membrane antigens that can be specifically recognized by therapeutic monoclonal antibodies, such as Rituximab (anti-CD20) in B-cell lymphomas and Trastuzumab (anti-HER2, human epidermal growth factor receptor 2) in breast cancer. Vitamin D deficient patients are poor responders to this therapy [134,135]. This suggests another mechanism of $1,25(\text{OH})_2\text{D}_3$ with a potential anti-tumoral relevance in the clinic, which is the enhancement of the antibody-dependent cellular cytotoxicity of macrophages and natural killer cells. Nevertheless, the main impact of the immune system in explaining the anti-cancer effect of vitamin D may not be in controlling and reducing settled tumors but in preventing their establishment. In an healthy individual every day thousands of cells undergo alterations that change from a normal to a malignant phenotype, but most of them are detected in this early stage by cytolytic T cells and destroyed [136]. Thus, an activation of cytolytic T cells may be an effective way how vitamin D prevents cancer onset [137].

In summary, there are many mechanisms through which the prime action of vitamin D, the modulation of innate and adaptive immunity, affects the growth, differentiation and apoptosis of cancer cells and explains the anti-cancer action of the nuclear hormone.

7. Vitamin D and CRC

A large number of mechanistic studies *in vitro* as well as in experimental animals support the beneficial action of VDR agonists, which had been suggested by epidemiology data that linked vitamin D deficiency to high incidence and/or mortality by CRC [138]. The regulation of more than thousand vitamin D target genes in colon carcinoma cells, normal stem cells, cancer stem cells, stromal NFs and CAFs as well as immune cells of the tumor microenvironment in combination with the tumor-inhibitory effects of vitamin D in xenografted mice strongly indicate a protection against this form of neoplasia (Fig. 3).

CRC is the best characterized solid neoplasia in terms of genetic alterations. Massive sequencing efforts have shown that over 94 % of primary and up to 96 % of metastatic colorectal tumors contain mutations in genes that aberrantly activate the WNT/ β -catenin signaling pathway [139,140]. Thus, mutually exclusive mutations of the genes

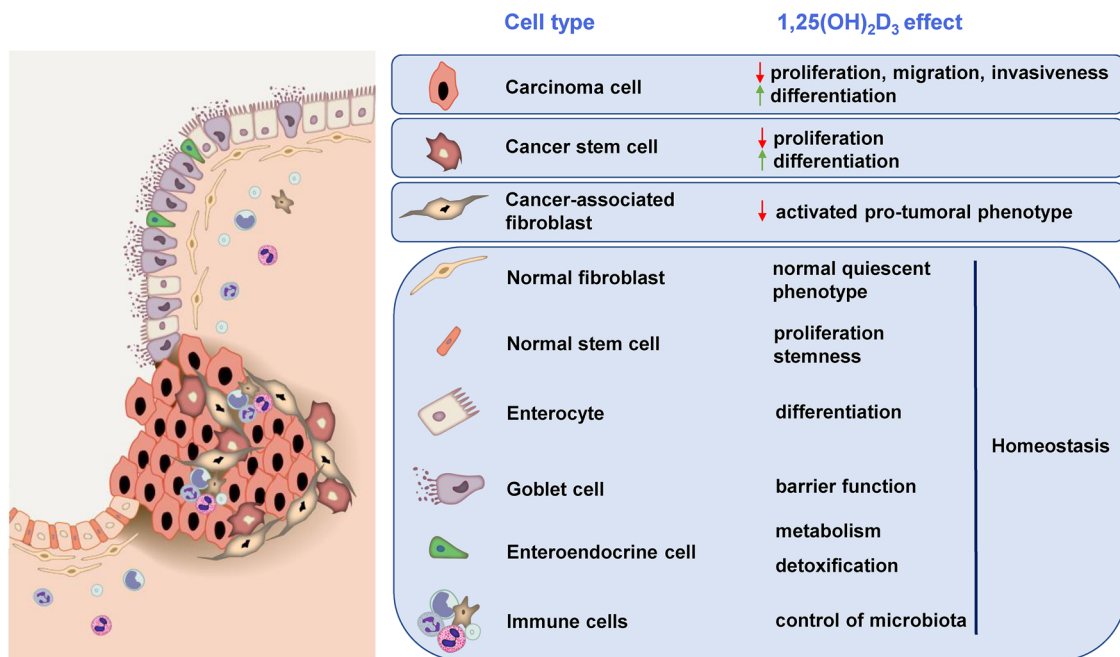


Fig. 3. Vitamin D effects in CRC. The scheme shows the topographic distribution of the cell types in the colon crypt. Effects of 1,25(OH)₂D₃ on the different cell types (tumor and stromal) in a colon neoplasia and in adjacent normal tissue. Homeostatic effects on normal cells and protective effects on tumor cells are indicated.

APC (APC regulator of WNT signaling pathway), *CTNNB1* (catenin beta 1) and *AXIN2* (axin 2) and less frequently of *RSPO2/3* (R-spondin 2 and 3), *RNF43* (ring finger protein 43) and *TCF7L2* (transcription factor 7 like 2) in colon epithelial (probably stem) cells are considered the initiation of the tumorigenic process.

1,25(OH)₂D₃ has two major effects on colon carcinoma cells: it inhibits the proliferation and promotes the differentiation through several mechanisms including i) the induction of VDR binding to β-catenin within the cell nucleus that prevent the formation of transcriptionally active TCF7L2/β-catenin complexes, ii) the up-regulation of the protein CDH1 (cadherin 1, also called E-cadherin) at the plasma membrane where it attracts the newly synthesized β-catenin protein and iii) the induction of the gene *DKK1* (Dickkopf WNT signaling pathway inhibitor 1) [141–143].

An important anti-proliferative mechanism of 1,25(OH)₂D₃ is the inhibition of the *MYC* gene, which is a major cell cycle regulator being induced by the WNT/β-catenin pathway and over-expressed in CRC as well as in many other cancer types. While nearly all CRCs have changes in *MYC* target genes, vitamin D represses the *MYC* gene directly by VDR binding to its promoter [144] and indirectly via inhibition of the WNT/β-catenin pathway [141], the induction of its antagonistic partner MAD/MXD1 of *MYC* [145] and the enhancement of its FBW7 E3 ligase-mediated ubiquitination and subsequent proteasomal degradation of the *MYC* protein [146]. 1,25(OH)₂D₃ regulates also other genes encoding cell cycle proteins or members of mitogenic pathways (Table 1). Another mode by which 1,25(OH)₂D₃ reduces cell proliferation is the interference of signaling by mitogens. Vitamin D reduces the expression and activity of the *EGFR* gene and also represses the *SPRY2* (sprouty RTK signaling antagonist 2) gene, which encodes an activator of intracellular EGF signaling [147–149]. Likewise, 1,25(OH)₂D₃ inhibits signaling by insulin growth factor (IGF) 2 protein.

These findings show that 1,25(OH)₂D₃ is a multi-level inhibitor of colon carcinoma cell proliferation via controlling a variety of genes and several mitogenic signaling pathways. Conceivably, this anti-tumoral mechanism is a secondary effect of the evolutionary selection of 1,25(OH)₂D₃ as a homeostatic regulator of the organism through the control of a large proportion of the human genome. Supporting this idea, in colon carcinoma cells 1,25(OH)₂D₃ also regulates genes involved in apoptosis, angiogenesis and migration/invasiveness as well as

in cell adhesion and differentiation (Table 1) [98,150,151].

Remarkably, epigenetic regulators, such as *KDM6B* and other histone demethylases [83,152] as well as *CST5* (cystatin D) are also under the control of 1,25(OH)₂D₃ [153,154]. *CST5* is a member of the cathepsin gene family encoding a multifunctional protein with protease activity in lysosomes and gene regulatory action within the cell nucleus. Moreover, several genes encoding enzymes and inhibitors of the ubiquitin-proteasome system are modulated by vitamin D in colon carcinoma cells suggesting that 1,25(OH)₂D₃ has a role in the post-translational control of gene expression [155]. Additional pathways affected by liganded VDR are detoxification and immunomodulation-related signaling, the latter probably both in carcinoma cells and in immune cells of the tumor microenvironment (Table 1) [102,108].

An indirect but potent mechanism of controlling the phenotype of colon carcinoma cells by 1,25(OH)₂D₃ is the regulation of miR-22, which contributes to the anti-proliferative and migratory actions of vitamin D and has also anti-tumor activity in several cancers [156].

The induction of an epithelial differentiated phenotype is a second major effect of 1,25(OH)₂D₃ in colon carcinoma cells. A key mechanism is the up-regulation of the *CDH1* gene [121], the encoded protein of which is the main component of adherens junctions being the most important structure responsible for intercellular adhesion in epithelia. The promotion of strong cell-to-cell adhesion, which reduces their capacity to proliferate, is further supported by the induction of other genes, *OCN* and *TJP1*, coding for components of additional adhesion structures, such as tight junctions and desmosomes [121] (Table 1).

Remarkably, a detailed study of the induction of the *CDH1* gene revealed a rapid, non-genomic signaling pathway triggered via extranuclear VDR [157]. 1,25(OH)₂D₃ increases cytosolic Ca²⁺ concentration in a transcription-independent way by favoring its entry from the external medium, which causes the cascade activation of RHOA (Ras homolog family member A), ROCK1 (Rho associated coiled-coil containing protein kinase 1) and the kinases MAPK14 (mitogen-activated protein kinase 14) and RPS6KA5 (ribosomal protein S6 kinase A5). Importantly, the induction of this pathway is necessary for the gene regulatory action of 1,25(OH)₂D₃ within the cell nucleus in a variety of cell types. This indicates a dual role of VDR and the convergence of non-genomic and genomic 1,25(OH)₂D₃ signaling pathways [157]. Thus, 1,25(OH)₂D₃ has a key role in the biology of colon epithelial cells

counteracting the genetic and epigenetic alterations that promote the apparition of colon carcinomas.

A large proportion of advanced CRC cases do not express the VDR gene, which is due to the up-regulation of the transcription factors SNAI1 (snail family transcriptional repressor 1) and SNAI2 that bind and block the VDR promoter region [158,159]. This suggests that VDR agonists have a protective effect in the prevention and early stages of CRC. However, a recent study [67] analyzing more than 600 CRC biopsies revealed that high VDR expression in CAFs associates with better clinical patient outcome. Moreover, 1,25(OH)₂D₃ imposes in primary CAF cultures a gene signature (48 genes) that is associated with longer patient survival [67]. Accordingly, 1,25(OH)₂D₃ regulates in these cells signaling pathways that are linked to a phenotype of activated fibroblasts by modulating of extracellular matrix and cytokine/chemokine-mediated cell migration and communication. As a result, 1,25(OH)₂D₃ attenuates two pro-tumoral effects of CAFs, which are their capacity to contract/alter the collagen gel and to promote the migration of carcinoma cells [67]. 1,25(OH)₂D₃ reprograms stromal fibroblasts towards a less pro-tumoral phenotype as already shown for liver and pancreas cancer [132,160]. This indicates that the beneficial actions of VDR agonists also affect stromal cells of the tumor micro-environment. Thus, CRC patients with VDR-negative carcinoma cells may still benefit from vitamin D treatment.

Based on the concept of Tomasetti and Vogelstein [161] 2/3 of all cancer mutations are based on replication errors, primarily of normal adult stem cells. A large part of these mutations are due to extrinsic factors, *i.e.*, they are based on lifestyle decisions, such as smoking and diet choice. However, until recently the effect of vitamin D on non-hematopoietic stem cells had not been studied. Therefore, a recent study [57] using organoids generated with healthy colon tissue from CRC patients became very important, as it indicated that 1,25(OH)₂D₃ inhibits cell proliferation and maintains the stem cell phenotype by increasing the expression of several stemness-related genes (*LGR5* (leucine rich repeat containing G protein-coupled receptor 5), *SMOC2*, *LRIG1*, *MEX3A*, *MSI1*, *PTK7*). In contrast, in matched tumor organoids of the same patients 1,25(OH)₂D₃ promotes cell differentiation with only minor changes in stemness genes. Moreover, vitamin D also causes a variable inhibitory effect on cell proliferation and the repression of genes linked to the tumorigenesis process. In contrast to carcinoma cells with an overactivated WNT/β-catenin pathway, 1,25(OH)₂D₃ does not affect WNT target genes in stem cell-derived organoids. In the latter, this signaling pathway plays a major role in the maintenance of stemness with EGF acting as the main mitogen. Thus, 1,25(OH)₂D₃ contributes to the preservation of the undifferentiated phenotype of crypt bottom adult stem cells and their basal level of proliferation, but, importantly, it attenuates their transformation into cancer stem cells. For example, feeding mice a purified rodent Western-style, low vitamin D diet perturbs intestinal cell maturation and WNT signaling and causes sporadic colon and small intestinal tumors. The diet acts as extrinsic factor and associates with extensive transcriptional reprogramming, such as decreasing the number of mouse *Lgr5*^{high} intestinal stem cells [162–164], and supports the role of vitamin D in controlling intestinal stem cells. Thus, the anti-cancer effect of vitamin D, in particular on CRC, may be primarily caused by its effects on adult stem cells.

Taken together, vitamin D modulates an ample array of signaling pathways in the diverse cell types involved in CRC (Fig. 3 and Table 1). Both the homeostatic nature of those promoted in normal adult stem cells and NFs and the anti-tumor nature of those induced in carcinoma cells, CAFs and cancer stem cells strongly indicate a strong, multi-level protective action of vitamin D against CRC.

8. Vitamin D and breast cancer

Data on the association of vitamin D and breast cancer incidence and/or mortality are inconclusive and less clear than for CRC [165]. However, two recent meta-analyses suggest a protective relationship

between 25(OH)D₃ serum levels (not vitamin D intake, emphasizing the importance of individual genetics and metabolism) and breast cancer risk [166,167]. Some studies [166], but not others [167], have found a preferential effect in pre-menopausal women. The controversial results reported may be, at least in part, due to the heterogeneity of breast cancer, which comprises several pathological and genetic subtypes. Interestingly, the triple-negative breast cancer (TNBC) subtype, which is characterized by the lack or low tumor expression of ER, PR and HER2 protein (ER⁻, PR⁻, HER2⁻) and a poor prognosis, may preferentially benefit from the protective effect of vitamin D [167,168]. Supporting this, TNBCs showing positive VDR staining correlate inversely with bad pathological features and directly with increased overall survival [169].

As for CRC, studies in cultured cells and animal models of breast cancer support a protective effect of VDR agonists, which appears to result from direct effects on tumor cells rather than on systemic actions or effects on stromal cells of the microenvironment [170]. Thus, treating breast cancer cell lines with 1,25(OH)₂D₃ induces anti-proliferative [171] as well as pro-apoptotic effects [172,173]. The former is linked to the suppression of growth stimulatory signals and genes (*MYC* and genes coding for cyclins and CDKs) and the potentiation of growth inhibitory signals and genes, whilst the latter is explained by *BCL2* (*BCL2* apoptosis regulator) family proteins. Moreover, 1,25(OH)₂D₃ favors the differentiated, non-invasive epithelial phenotype of breast tumor cells by both inducing genes, such as *CDH1*, while repressing those encoding for N- and P-cadherins (*CDH2* and *CDH3*) and others [174–176] (Table 1). Thus, as in CRC, *MYC* and *CDH1* seem to be crucial target genes of 1,25(OH)₂D₃ in breast carcinoma cells.

Other studies, however, proposed tumor non-autonomous effects of vitamin D on breast cancer. For example, 1,25(OH)₂D₃ reduces the adverse effects of obesity on breast cancer by acting on pathways both within breast cancer cells and surrounding adipocytes by suppressing estrogen synthesis and signaling via the control of prostaglandin E₂ synthesis by PTGS2 (prostaglandin-endoperoxide synthase 2) and degradation, and the inhibition of ER and PTGER2 (prostaglandin E receptor 2) and CYP19A1 (aromatase) [177,178]. Giving the important role of estradiol promoting the proliferation of breast cancer cells at least at early stages of tumor development, these effects on estrogen signaling may protect against breast cancer at the initial steps. In addition, 1,25(OH)₂D₃ enhances AMPK (adenosine monophosphate-activated protein kinase) signaling and restores the adipokine profile by decreasing leptin signaling and stimulating adiponectin signaling that are dys-regulated in response to diet-induced obesity in both tumor cells and surrounding adipose tissue.

Finally, 1,25(OH)₂D₃ inhibits spheroid formation by mouse breast tumor-initiating cells by down-regulating ER [179]. Likewise, 1,25(OH)₂D₃ inhibits mammosphere formation in cultures of MCF10DCIS and SUM159 breast cancer cell lines by down-regulating the expression of stem cell markers and several NOTCH pathway genes [180].

In summary, the effects of vitamin D on breast cancer are partially similar to but overall less convincing than those on CRC. Moreover, the effect, if any, of 1,25(OH)₂D₃ on authentic human breast cancer stem cells remains to be elucidated.

9. Vitamin D and prostate cancer

The association between vitamin D status and prostate cancer is much less compelling than those for colorectal or breast cancer suggesting that not all tissues or cancer cell types respond identically. While some studies found a direct relation between circulating 25(OH)D₃ and prostate cancer risk or mortality, others did not, and even a few reported that high levels of 25(OH)D₃ are associated with increased risk, altogether leading to inconclusive meta-analyses [181,182]. A limited number of interventional clinical trials using vitamin D compounds as single agents or in combination have been seriously criticized

for bad design and flawed conclusions [183]. Still, data from pre-clinical studies on the effect of vitamin D in prostate cells and animal models do not differ much from those in other cancer types. In addition to the usual anti-proliferative and apoptotic-sensitization effects, $1,25(\text{OH})_2\text{D}_3$ has in prostate cancer regulatory actions on *PTGS2* and other genes of the prostaglandin pathway as well as on *IL6* suggesting an anti-inflammatory effect [184]. Moreover, $1,25(\text{OH})_2\text{D}_3$ activates in prostate cancer cells metabolic enzymes, such as *CYP3A4*, *CYP3A5*, *UGT2B15/17* and *SULT2B1*, that may reduce the availability of androgens acting as mitogens in these cells.

A microarray study in the human non-transformed RWPE1 prostate epithelial cell line showed that $1,25(\text{OH})_2\text{D}_3$ regulates a high number of genes suggestive of the suppression of cancer- and inflammation-related signaling pathways (WNT, NOTCH, NF- κ B, IGF1, IL1, IL6, IL17) and the induction of protection from oxidative stress [185]. Concordantly, in the TgAPT₁₂₁ mouse model of prostate cancer dietary vitamin D reduces the apparition of adenocarcinomas whereas the loss of the *Vdr* gene accelerates the early stages of prostate carcinogenesis [53]. In this system, microarray and ChIP-seq analysis identified thousands of target genes, some of which are involved in cell cycle and proliferation (*FOS*, *EGR1*, *MAPK8*, *HGF*, *MYC*), apoptosis (*FOXO1*, *SRF*, *CALM2*), cell adhesion (*EPHB1*, *EPHA2*, *MLCK*), immune response (*CCL16*, *IL6*, *IFNG*) and gene transcription/expression (*HIF1A*, *SMAD3*, *CREB1*, *CREM*, *CBF1*, *ESR1*). Interestingly, in another model of prostate cancer, TRAMP mice, early treatment with vitamin D slowed androgen-stimulated tumor progression by reducing tumor cell proliferation and inducing E-cadherin but in long-term increased distant organ metastasis [186].

Taken together, prostate cancer is complex with an intricate hormonal regulation and multiple cell types involved. Still much work is needed to elucidate the mechanisms and potential utility of vitamin D in this neoplasia.

10. Vitamin D and hematological malignancies

As it happens in solid tumors, patients with hematological malignancies, such as leukemias, lymphomas and multiple myeloma, usually have a low vitamin D status being associated with a poorer prognosis [187–190]. As in other cancer cell types, VDR agonists inhibit proliferation (AML, B cell acute lymphoblastic leukemia, follicular non-Hodgkin's lymphoma), sensitize to apoptosis promoted by signals including other anti-tumor therapies (AML, cutaneous T lymphoma, multiple myeloma, diffuse large B cell lymphoma, B cell chronic lymphocytic leukemia), induce differentiation (AML, follicular non-Hodgkin's lymphoma) and usually decrease the production of pro-inflammatory cytokines [191]. $1,25(\text{OH})_2\text{D}_3$ decreases the activation of the Janus kinase (JAK)-signal transducers and activators of transcription (STAT) signaling pathway, as revealed by diminution of the level of phospho-STAT3 and phospho-STAT1. This pathway is commonly overactivated in leukemia and lymphoma cells due to mutation in JAKs or STATs or by abnormally high cytokine signaling. As a consequence, $1,25(\text{OH})_2\text{D}_3$ decreases the production of the cytokines IFNG (interferon gamma), TNF (tumor necrosis factor) and several interleukins [192].

AML is a heterogeneous group of leukemias that result from clonal transformation of hematopoietic precursors through the acquisition of chromosomal rearrangements and multiple gene mutations. As AML cells are proliferatively immature, differentiation therapy is potentially effective for initiation of terminal differentiation and represents a supplementary approach for the treatment of neoplastic disease in combination with existing treatment modalities [193]. Importantly, $1,25(\text{OH})_2\text{D}_3$ initiates differentiation in AML cell lines, such as HL60, which are predominantly neutrophilic promyelocytes. Treatment of HL60 cells with $1,25(\text{OH})_2\text{D}_3$ results in a reduced proliferation and enhanced differentiation along the monocyte-macrophage pathway possibly by mechanisms involving the up-regulation of *CEBPD* [194,195]. Moreover, together with the pioneer factors CEBPA and

PU.1 VDR is the key regulator of the differentiation of monocytes and granulocytes [88] probably via the induction of the *CDKN1A* gene [196]. Interestingly, in a zebrafish model it had been shown that vitamin D regulates the number of embryonal hematopoietic stem cells [44]. This observation was confirmed *ex vivo* with human hematopoietic stem cells possibly via the induction of the gene *CXCL8* (C-X-C motif chemokine ligand 8) that is known as a primary vitamin D target [197]. This suggests that vitamin D first pushes the growth of hematopoietic stem cells and then induces their differentiation into myeloid cells. Accordingly, in the context of hematopoietic stem cell transplants vitamin D deficiency is known to be associated with increased complications, such as graft-versus-host disease, delayed time to neutrophil engraftment and overall survival [198,199].

A recent mice study showed that *Vdr* deficiency in hematopoietic precursors causes an increase in the expression of the genes *MECOM* (MDS1 and EVI1 complex locus), *HOXA9* (homeobox A9) and *MEIS1* (meis homeobox 1) suggesting the induction of an immature phenotype and, concordantly, of the number leukemia stem cells and normal hematopoietic stem cells [200].

In summary, VDR is a new genetic modifier contributing to the expression of different subtypes of acute myeloid leukemia, *i.e.*, vitamin D plays an important role in normal but also in pathological hematopoiesis.

11. Conclusion

Epigenomic and transcriptomic analyses as well as numerous experimental studies in a variety of cancer systems provided large sets of strong data that jointly indicate a protective action of vitamin D signaling against several types of cancer. Most convincing molecular data exist for CRC and AML. This results from the regulation of a high number of genes that control the proliferation, survival, differentiation, migration and communication of cancer cells and stromal cells, such as fibroblasts, adipocytes, immune and endothelial cells. Conceivable, the lack of concordant positive clinical data in large randomized controlled trials may be due to lack of sub-analysis of disease cohorts (*e.g.*, the selection and analysis of patients) as well as short follow-up. Moreover, the careful characterization of disease subgroups should lead to more consistent data as shown for TNBC. Vitamin D is a major regulator of signaling in human cells, which displays a long list of protective homeostatic effects in cultured cells and animal models of cancer. Thus, it contributes to maintain and defend the normal physiology of the organism against the apparition and development of neoplasias. The identification of the optimal clinical use of the vitamin D system is a task demanding continuous efforts.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The work in the authors' laboratories is supported by the Academy of Finland (CC) and Ministerio de Ciencia e Innovación of Spain-Fondo Europeo de Desarrollo Regional (FEDER) (SAF2016-76377-R, SAF2017-90604-REDT/Nurcamin) and Instituto de Salud Carlos III-FEDER (CIBERONC; CB16/12/00273) (AM).

References

- [1] M. De Palma, D. Hanahan, The biology of personalized cancer medicine: facing individual complexities underlying hallmark capabilities, *Mol. Oncol.* 6 (2012) 111–127.
- [2] D. Hanahan, R.A. Weinberg, Hallmarks of cancer: the next generation, *Cell* 144 (2011) 646–674.
- [3] B. Vogelstein, N. Papadopoulos, V.E. Velculescu, S. Zhou, L.A. Diaz Jr., K.W. Kinzler, Cancer genome landscapes, *Science* 339 (2013) 1546–1558.

- [4] C. Carlberg, F. Molnár, Human Epigenomics, Springer Textbook, 2018.
- [5] R.R. Kanherkar, N. Bhatia-Dey, A.B. Csoka, Epigenetics across the human lifespan, *Front. Cell Dev. Biol.* 2 (2014) 49.
- [6] F. Bray, J. Ferlay, I. Soerjomataram, R.L. Siegel, L.A. Torre, A. Jemal, Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries, *CA Cancer J. Clin.* 68 (2018) 394–424.
- [7] W.B. Grant, M. Moukayed, Vitamin D₃ from ultraviolet-B exposure or oral intake in relation to cancer incidence and mortality, *Curr. Nutr. Rep.* 8 (2019) 203–211.
- [8] K. Kupferschmidt, Uncertain verdict as vitamin D goes on trial, *Science* 337 (2012) 1476–1478.
- [9] M.F. Holick, J.E. Frommer, S.C. McNeill, N.M. Richtand, J.W. Henley, J.T. Potts Jr., Photometabolism of 7-dehydrocholesterol to previtamin D₃ in skin, *Biochem. Biophys. Res. Commun.* 76 (1977) 107–114.
- [10] J.E. Zerwekh, Blood biomarkers of vitamin D status, *Am. J. Clin. Nutr.* 87 (2008) 1087S–91S.
- [11] I. Bendik, A. Friedel, F.F. Roos, P. Weber, M. Eggersdorfer, Vitamin D: a critical and essential micronutrient for human health, *Front. Physiol.* 5 (2014) 248.
- [12] B. Dawson-Hughes, R.P. Heaney, M.F. Holick, P. Lips, P.J. Meunier, R. Vieth, Estimates of optimal vitamin D status, *Osteoporos. Int.* 16 (2005) 713–716.
- [13] M.R. Haussler, P.W. Jurutka, M. Mizwicki, A.W. Norman, Vitamin D receptor (VDR)-mediated actions of 1 α ,25(OH)₂vitamin D₃: genomic and non-genomic mechanisms, *Best Pract. Res. Clin. Endocrinol. Metab.* 25 (2011) 543–559.
- [14] C. Carlberg, Molecular endocrinology of vitamin D on the epigenome level, *Mol. Cell. Endocrinol.* 453 (2017) 14–21.
- [15] C.S. Hii, A. Ferrante, The non-genomic actions of vitamin D, *Nutrients* 8 (2016) 135.
- [16] K.K. Deeb, D.L. Trump, C.S. Johnson, Vitamin D signalling pathways in cancer: potential for anticancer therapeutics, *Nat. Rev. Cancer* 7 (2007) 684–700.
- [17] J.C. Fleet, M. DeSmet, R. Johnson, Y. Li, Vitamin D and cancer: a review of molecular mechanisms, *Biochem. J.* 441 (2012) 61–76.
- [18] D. Feldman, A.V. Krishnan, S. Swami, E. Giovannucci, B.J. Feldman, The role of vitamin D in reducing cancer risk and progression, *Nat. Rev. Cancer* 14 (2014) 342–357.
- [19] C.F. Garland, F.C. Garland, Do sunlight and vitamin D reduce the likelihood of colon cancer? *Int. J. Epidemiol.* 9 (1980) 227–231.
- [20] K.W. Colston, M.J. Colston, D. Feldman, 1,25-dihydroxyvitamin D₃ and malignant melanoma: the presence of receptors and inhibition of cell growth in culture, *Endocrinology* 108 (1981) 1083–1086.
- [21] C.F. Garland, F.C. Garland, E.D. Gorham, M. Lipkin, H. Newmark, S.B. Mohr, M.F. Holick, The role of vitamin D in cancer prevention, *Am. J. Public Health* 96 (2006) 252–261.
- [22] K. Ng, H.S. Nimeiri, N.J. McCleary, T.A. Abrams, M.B. Yurgelun, J.M. Cleary, D.A. Rubinson, D. Schrag, R. Miksad, A.J. Bullock, J. Allen, D. Zuckerman, E. Chan, J.A. Chan, B.M. Wolpin, M. Constantine, D.J. Weckstein, M.A. Faggen, C.A. Thomas, C. Kourmlioti, C. Yuan, C. Ganser, B. Wilkinson, C. Mackintosh, H. Zheng, B.W. Hollis, J.A. Meyerhardt, C.S. Fuchs, Effect of highdose vs standard-dose vitamin D₃ supplementation on progression-free survival among patients with advanced or metastatic colorectal cancer: the SUNSHINE randomized clinical trial, *JAMA* 321 (2019) 1370–1379.
- [23] A. Markotic, S. Langer, T. Kelava, K. Vucic, P. Turcic, T. Tokic, L. Stefancic, E. Radetic, S. Farrington, M. Timofeova, I. Rudan, H. Campbell, M. Dunlop, I. Kirac, L. Zgaga, Higher post-operative serum vitamin D level is associated with better survival outcome in colorectal cancer patients, *Nutr. Cancer* 71 (2019) 1078–1085.
- [24] A.H. Calderwood, J.A. Baron, L.A. Mott, D.J. Ahnen, R.M. Bostick, J.C. Figueiredo, M.N. Passarelli, J.R. Rees, D.J. Robertson, E.L. Barry, No evidence for posttreatment effects of vitamin D and calcium supplementation on risk of colorectal adenomas in a randomized trial, *Cancer Prev. Res. (Phila)* 12 (2019) 295–304.
- [25] J.E. Manson, N.R. Cook, I.M. Lee, W. Christen, S.S. Bassuk, S. Mora, H. Gibson, D. Gordon, T. Copeland, D. D'Agostino, G. Friedenber, C. Ridge, V. Bubes, E.L. Giovannucci, W.C. Willett, J.E. Buring, V.R. Group, Vitamin D supplements and prevention of cancer and cardiovascular disease, *N. Engl. J. Med.* 380 (2019) 33–44.
- [26] W.B. Grant, B.J. Boucher, Why secondary analyses in vitamin D clinical trials are important and how to improve vitamin D clinical trial outcome analyses, *Nutrients* 11 (2019) E2182.
- [27] N. Keum, E. Giovannucci, Vitamin D supplements and cancer incidence and mortality: a meta-analysis, *Br. J. Cancer* 111 (2014) 976–980.
- [28] J. Wactawski-Wende, J.M. Kotchen, G.L. Anderson, A.R. Assaf, R.L. Brunner, M.J. O'Sullivan, K.L. Margolis, J.K. Ockene, L. Phillips, L. Pottern, R.L. Prentice, J. Robbins, T.E. Rohan, G.E. Sarto, S. Sharma, M.L. Stefanick, L. Van Horn, R.B. Wallace, E. Whitlock, T. Bassford, S.A. Beresford, H.R. Black, D.E. Bonds, R.G. Brzyski, B. Caan, R.T. Chlebowski, B. Cochrane, C. Garland, M. Gass, J. Hays, G. Heiss, S.L. Hendrix, B.V. Howard, J. Hsia, F.A. Hubbell, R.D. Jackson, K.C. Johnson, H. Judd, C.L. Kooperberg, L.H. Kuller, A.Z. LaCroix, D.S. Lane, R.D. Langer, N.L. Lasser, C.E. Lewis, M.C. Limacher, J.E. Manson, I. Women's Health Initiative, Calcium plus vitamin D supplementation and the risk of colorectal cancer, *N. Engl. J. Med.* 354 (2006) 684–696.
- [29] A. Avenell, G.S. MacLennan, D.J. Jenkinson, G.C. McPherson, A.M. McDonald, P.R. Pant, A.M. Grant, M.K. Campbell, F.H. Anderson, C. Cooper, R.M. Francis, W.J. Gillespie, C.M. Robinson, D.J. Torgerson, W.A. Wallace, R.T. Group, Long-term follow-up for mortality and cancer in a randomized placebo-controlled trial of vitamin D₃ and/or calcium (RECORD trial), *J. Clin. Endocrinol. Metab.* 97 (2012) 614–622.
- [30] D.P. Trivedi, R. Doll, K.T. Khaw, Effect of four monthly oral vitamin D₃ (cholecalciferol) supplementation on fractures and mortality in men and women living in the community: randomised double blind controlled trial, *BMJ* 326 (2003) 469.
- [31] C. Carlberg, A. Haq, The concept of the personal vitamin D response index, *J. Steroid Biochem. Mol. Biol.* 175 (2018) 12–17.
- [32] M. Vukic, A. Neme, S. Seuter, N. Saksa, V.D. de Mello, T. Nurmi, M. Uusitupa, T.P. Tuomainen, J.K. Virtanen, C. Carlberg, Relevance of vitamin D receptor target genes for monitoring the vitamin D responsiveness of primary human cells, *PLoS One* 10 (2015) e0124339.
- [33] S. Seuter, J.K. Virtanen, T. Nurmi, J. Pihlajamäki, J. Mursu, S. Voutilainen, T.P. Tuomainen, A. Neme, C. Carlberg, Molecular evaluation of vitamin D responsiveness of healthy young adults, *J. Steroid Biochem. Mol. Biol.* 174 (2017) 314–321.
- [34] W.B. Grant, B.J. Boucher, H.P. Bhattoa, H. Lahore, Why vitamin D clinical trials should be based on 25-hydroxyvitamin D concentrations, *J. Steroid Biochem. Mol. Biol.* 177 (2018) 266–269.
- [35] R.M. Evans, The nuclear receptor superfamily: a rosetta stone for physiology, *Mol. Endocrinol.* 19 (2005) 1429–1438.
- [36] D.J. Mangelsdorf, C. Thummel, M. Beato, P. Herrlich, G. Schütz, K. Umesono, B. Blumberg, P. Kastner, M. Mark, P. Chambon, R.M. Evans, The nuclear receptor superfamily: the second decade, *Cell* 83 (1995) 835–839.
- [37] C. Carlberg, F. Molnár, Current status of vitamin D signaling and its therapeutic applications, *Curr. Top. Med. Chem.* 12 (2012) 528–547.
- [38] F. Molnár, M. Peräkylä, C. Carlberg, Vitamin D receptor agonists specifically modulate the volume of the ligand-binding pocket, *J. Biol. Chem.* 281 (2006) 10516–10526.
- [39] M.R. Haussler, C.A. Haussler, P.W. Jurutka, P.D. Thompson, J.C. Hsieh, L.S. Remus, S.H. Selznick, G.K. Whitfield, The vitamin D hormone and its nuclear receptor: molecular actions and disease states, *J. Endocrinol.* 154 (Suppl) (1997) S57–73.
- [40] G.K. Whitfield, H.T. Dang, S.F. Schluter, R.M. Bernstein, T. Bunag, L.A. Manzoni, G. Hsieh, C.E. Dominguez, J.H. Youson, M.R. Haussler, J.J. Marchalonis, Cloning of a functional vitamin D receptor from the lamprey (*Petromyzon marinus*), an ancient vertebrate lacking a calcified skeleton and teeth, *Endocrinology* 144 (2003) 2704–2716.
- [41] A. Hanel, C. Carlberg, Vitamin D and evolution: pharmacologic implications, *Biochem. Pharmacol.* 173 (2020) 113595.
- [42] V. Muller, R.J. de Boer, S. Bonhoeffer, E. Szathmary, An evolutionary perspective on the systems of adaptive immunity, *Biol. Rev. Camb. Philos. Soc.* 93 (2018) 505–528.
- [43] A.S. Vanherwegen, C. Gysemans, C. Mathieu, Vitamin D endocrinology on the cross-road between immunity and metabolism, *Mol. Cell. Endocrinol.* 453 (2017) 52–67.
- [44] M. Cortes, M.J. Chen, D.L. Stachura, S.Y. Liu, W. Kwan, F. Wright, L.T. Vo, L.N. Theodore, V. Esain, I.M. Frost, T.M. Schlaeger, W. Goessling, G.Q. Daley, T.E. North, Developmental vitamin D availability impacts hematopoietic stem cell production, *Cell Rep.* 17 (2016) 458–468.
- [45] R. Bouillon, T. Suda, Vitamin D: Calcium and bone homeostasis during evolution, *Bonekey Rep.* 3 (2014) 480.
- [46] V. Veldurthy, R. Wei, L. Oz, P. Dhawan, Y.H. Jeon, S. Christakos, Vitamin D, calcium homeostasis and aging, *Bone Res.* 4 (2016) 16041.
- [47] M.F. Holick, Resurrection of vitamin D deficiency and rickets, *J. Clin. Invest.* 116 (2006) 2062–2072.
- [48] J. van de Peppel, J.P. van Leeuwen, Vitamin D and gene networks in human osteoblasts, *Front. Physiol.* 5 (2014) 137.
- [49] M.D. Long, M.J. Campbell, Integrative genomic approaches to dissect clinically-significant relationships between the VDR cistrome and gene expression in primary colon cancer, *J. Steroid Biochem. Mol. Biol.* 173 (2017) 130–138.
- [50] S.V. Ramagopalan, A. Heger, A.J. Berlanga, N.J. Mauget, M.R. Lincoln, A. Burrell, L. Handunnetthi, A.E. Handel, G. Disanto, S.M. Orton, C.T. Watson, J.M. Morahan, G. Giovannoni, C.P. Ponting, G.C. Ebers, J.C. Knight, A ChIP-seq defined genome-wide map of vitamin D receptor binding: associations with disease and evolution, *Genome Res.* 20 (2010) 1352–1360.
- [51] G. Gallone, W. Haerty, G. Disanto, S.V. Ramagopalan, C.P. Ponting, A.J. Berlanga-Taylor, Identification of genetic variants affecting vitamin D receptor binding and associations with autoimmune disease, *Hum. Mol. Genet.* 26 (2017) 2164–2176.
- [52] N. Ding, R.T. Yu, N. Subramaniam, M.H. Sherman, C. Wilson, R. Rao, M. Leblanc, S. Coulter, M. He, C. Scott, S.L. Lau, A.R. Atkins, G.D. Barish, J.E. Gunton, C. Liddle, M. Downes, R.M. Evans, A vitamin D receptor/SMAD genomic circuit gates hepatic fibrotic response, *Cell* 153 (2013) 601–613.
- [53] J.C. Fleet, P.L. Kovalenko, Y. Li, J. Smolinski, C. Spees, J.G. Yu, J.M. Thomas-Ahner, M. Cui, A. Neme, C. Carlberg, S.K. Clinton, Vitamin D signaling suppresses early prostate carcinogenesis in TgAPT121 mice, *Cancer Prev. Res. (Phila)* 12 (2019) 343–356.
- [54] S. Heikkinen, S. Väisänen, P. Pehkonen, S. Seuter, V. Benes, C. Carlberg, Nuclear hormone 1 α ,25-dihydroxyvitamin D₃ elicits a genome-wide shift in the locations of VDR chromatin occupancy, *Nucleic Acids Res.* 39 (2011) 9181–9193.
- [55] A. Neme, S. Seuter, C. Carlberg, Selective regulation of biological processes by vitamin D based on the spatio-temporal cistrome of its receptor, *Biochim. Biophys. Acta* 1860 (2017) 952–961.
- [56] M.B. Meyer, P.D. Goetsch, J.W. Pike, VDR/RXR and TCF4/beta-catenin cistromes in colonic cells of colorectal tumor origin: impact on c-FOS and c-MYC gene expression, *Mol. Endocrinol.* 26 (2012) 37–51.
- [57] A. Fernandez-Barral, A. Costales-Carrera, S.P. Buirra, P. Jung, G. Ferrer-Mayorga, M.J. Larriba, P. Bustamante-Madrid, O. Dominguez, F.X. Real, L. Guerra-Pastrian, M. Lafarga, D. Garcia-Olmo, R. Cantero, L. Del Peso, E. Batlle, F. Rojo, A. Munoz, A. Labachano, Vitamin D differentially regulates colon stem cells in patient-derived normal and tumor organoids, *FEBS J.* 287 (2020) 53–72.

- [58] R. Kreienkamp, M. Croke, M.A. Neumann, G. Bedia-Diaz, S. Graziano, A. Dusso, D. Dorsett, C. Carlberg, S. Gonzalo, Vitamin D receptor signaling improves Hutchinson-Gilford progeria syndrome cellular phenotypes, *Oncotarget* (2016) 30018–30031.
- [59] M.B. Meyer, N.A. Benkusky, M. Kaufmann, S.M. Lee, R.R. Redfield, G. Jones, J.W. Pike, Targeted genomic deletions identify diverse enhancer functions and generate a kidney-specific, endocrine-deficient Cyp27b1 pseudo-null mouse, *J. Biol. Chem.* 294 (2019) 9518–9535.
- [60] C. Carlberg, Vitamin D signaling in the context of innate immunity: focus on human monocytes, *Front. Immunol.* 10 (2019) 2211.
- [61] G. Jones, D.E. Prosser, M. Kaufmann, Cytochrome P450-mediated metabolism of vitamin D, *J. Lipid Res.* 55 (2014) 13–31.
- [62] M. Tannour-Louet, S.K. Lewis, J.F. Louet, J. Stewart, J.B. Addai, A. Sahin, H.V. Vangapandu, A.L. Lewis, K. Dittmar, R.G. Pautler, L. Zhang, R.G. Smith, D.J. Lamb, Increased expression of CYP24A1 correlates with advanced stages of prostate cancer and can cause resistance to vitamin D3-based therapies, *FASEB J.* 28 (2014) 364–372.
- [63] P. Tuoresmäki, S. Väisänen, A. Neme, S. Heikkinen, C. Carlberg, Patterns of genome-wide VDR locations, *PLoS One* 9 (2014) e96105.
- [64] C. Carlberg, Genome-wide (over)view on the actions of vitamin D, *Front. Physiol.* 5 (2014) 167.
- [65] M.J. Campbell, Vitamin D and the RNA transcriptome: more than mRNA regulation, *Front. Physiol.* 5 (2014) 181.
- [66] C. Kriebitzsch, L. Verlinden, G. Eelen, B.K. Tan, M. Van Camp, R. Bouillon, A. Verstuyf, The impact of 1,25(OH)₂D₃ and its structural analogs on gene expression in cancer cells—a microarray approach, *Anticancer Res.* 29 (2009) 3471–3483.
- [67] G. Ferrer-Mayorga, G. Gomez-Lopez, A. Barbachano, A. Fernandez-Barral, C. Pena, D.G. Pisano, R. Cantero, F. Rojo, A. Munoz, M.J. Larriba, Vitamin D receptor expression and associated gene signature in tumour stromal fibroblasts predict clinical outcome in colorectal cancer, *Gut* 66 (2017) 1449–1462.
- [68] C.T. Wu, J.R. Morris, Genes, genetics, and epigenetics: a correspondence, *Science* 293 (2001) 1103–1105.
- [69] Chloe M. Rivera, B. Ren, Mapping human epigenomes, *Cell* 155 (2013) 39–55.
- [70] O.J. Rando, H.Y. Chang, Genome-wide views of chromatin structure, *Annu. Rev. Biochem.* 78 (2009) 245–271.
- [71] C. Carlberg, F. Molnár, The impact of chromatin, *Mechanisms of Gene Regulation*, 2nd ed., Springer, 2016, pp. 17–34.
- [72] M.P. Creighton, A.W. Cheng, G.G. Welstead, T. Kooistra, B.W. Carey, E.J. Steine, J. Hanna, M.A. Lodato, G.M. Frampton, P.A. Sharp, L.A. Boyer, R.A. Young, R. Jaenisch, Histone H3K27ac separates active from poised enhancers and predicts developmental state, *Proc. Natl. Acad. Sci. U. S. A.* 107 (2010) 21931–21936.
- [73] ENCODE-Project-Consortium, B.E. Bernstein, E. Birney, I. Dunham, E.D. Green, C. Gunter, M. Snyder, An integrated encyclopedia of DNA elements in the human genome, *Nature* 489 (2012) 57–74.
- [74] V. Haberle, A. Stark, Eukaryotic core promoters and the functional basis of transcription initiation, *Nat. Rev. Mol. Cell Biol.* 19 (2018) 621–637.
- [75] C. Beisel, R. Paro, Silencing chromatin: comparing modes and mechanisms, *Nat. Rev. Genet.* 12 (2011) 123–135.
- [76] Z.D. Smith, A. Meissner, DNA methylation: roles in mammalian development, *Nat. Rev. Genet.* 14 (2013) 204–220.
- [77] S. Sharma, T.K. Kelly, P.A. Jones, Epigenetics in cancer, *Carcinogenesis* 31 (2010) 27–36.
- [78] S.L. Klemm, Z. Shipony, W.J. Greenleaf, Chromatin accessibility and the regulatory epigenome, *Nat. Rev. Genet.* 20 (2019) 207–220.
- [79] S. Seuter, A. Neme, C. Carlberg, Epigenome-wide effects of vitamin D and their impact on the transcriptome of human monocytes involve CTCF, *Nucleic Acids Res.* 44 (2016) 4090–4104.
- [80] V. Nurminen, A. Neme, S. Seuter, C. Carlberg, The impact of the vitamin D-modulated epigenome on VDR target gene regulation, *Biochim. Biophys. Acta* 1861 (2018) 697–705.
- [81] F. Molnár, Structural considerations of vitamin D signaling, *Front. Physiol.* 5 (2014) 191.
- [82] Z. Wei, E. Yoshihara, N. He, N. Hah, W. Fan, A.F.M. Pinto, T. Huddy, Y. Wang, B. Ross, G. Estepa, Y. Dai, N. Ding, M.H. Sherman, S. Fang, X. Zhao, C. Liddle, A.R. Atkins, R.T. Yu, M. Downes, R.M. Evans, Vitamin D switches BAF complexes to protect beta cells, *Cell* 173 (2018) 1135–1149 e15.
- [83] F. Pereira, A. Barbachano, J. Silva, F. Bonilla, M.J. Campbell, A. Munoz, M.J. Larriba, KDM6B/JMJD3 histone demethylase is induced by vitamin D and modulates its effects in colon cancer cells, *Hum. Mol. Genet.* 20 (2011) 4655–4665.
- [84] S. Seuter, A. Neme, C. Carlberg, Epigenome PU.1-VDR crosstalk modulates vitamin D signaling, *Biochim. Biophys. Acta* 1860 (2017) 405–415.
- [85] V. Nurminen, A. Neme, S. Seuter, C. Carlberg, Modulation of vitamin D signaling by the pioneer factor CEBPA, *Biochim. Biophys. Acta* 1862 (2019) 96–106.
- [86] S. Seuter, A. Neme, C. Carlberg, ETS transcription factor family member GABPA contributes to vitamin D receptor target gene regulation, *J. Steroid Biochem. Mol. Biol.* 177 (2018) 46–52.
- [87] K.S. Zaret, S.E. Mango, Pioneer transcription factors, chromatin dynamics, and cell fate control, *Curr. Opin. Genet. Dev.* 37 (2016) 76–81.
- [88] N. Novershtern, A. Subramanian, L.N. Lawton, R.H. Mak, W.N. Haining, M.E. McConkey, N. Habib, N. Yosef, C.Y. Chang, T. Shay, G.M. Frampton, A.C. Drake, I. Leskov, B. Nilsson, F. Preffer, D. Dombkowski, J.W. Evans, T. Liefeld, J.S. Smutko, J. Chen, N. Friedman, R.A. Young, T.R. Golub, A. Regev, B.L. Ebert, Densely interconnected transcriptional circuits control cell states in human hematopoiesis, *Cell* 144 (2011) 296–309.
- [89] A. Neme, S. Seuter, C. Carlberg, Vitamin D-dependent chromatin association of CTCF in human monocytes, *Biochim. Biophys. Acta* 1859 (2016) 1380–1388.
- [90] C.T. Ong, V.G. Corces, CTCF: an architectural protein bridging genome topology and function, *Nat. Rev. Genet.* 15 (2014) 234–246.
- [91] J.R. Dixon, I. Jung, S. Selvaraj, Y. Shen, J.A. Antosiewicz-Bourget, A.Y. Lee, Z. Ye, A. Kim, N. Rajagopal, W. Xie, Y. Diao, J. Liang, H. Zhao, V.V. Lobanenko, J.R. Ecker, J.A. Thomson, B. Ren, Chromatin architecture reorganization during stem cell differentiation, *Nature* 518 (2015) 331–336.
- [92] M. Vietri Rudan, C. Barrington, S. Henderson, C. Ernst, D.T. Odum, A. Tanay, S. Hadjir, Comparative Hi-C reveals that CTCF underlies evolution of chromosomal domain architecture, *Cell Rep.* 10 (2015) 1297–1309.
- [93] J.R. Dixon, S. Selvaraj, F. Yue, A. Kim, Y. Li, Y. Shen, M. Hu, J.S. Liu, B. Ren, Topological domains in mammalian genomes identified by analysis of chromatin interactions, *Nature* 485 (2012) 376–380.
- [94] C. Carlberg, A. Neme, Machine learning approaches infer vitamin D signaling: critical impact of vitamin D receptor binding within topologically associated domains, *J. Steroid Biochem. Mol. Biol.* 185 (2019) 103–109.
- [95] V. Nurminen, S. Seuter, C. Carlberg, Primary vitamin D target genes of human monocytes, *Front. Physiol.* 10 (2019) 194.
- [96] A. Saramäki, C.M. Banwell, M.J. Campbell, C. Carlberg, Regulation of the human p21^{waf1/cip1} gene promoter via multiple binding sites for p53 and the vitamin D₃ receptor, *Nucleic Acids Res.* 34 (2006) 543–554.
- [97] A. Saramäki, S. Diermeier, R. Kellner, H. Laitinen, S. Väisänen, C. Carlberg, Cyclical chromatin looping and transcription factor association on the regulatory regions of the p21 (CDKN1A) gene in response to 1 α ,25-dihydroxyvitamin D₃, *J. Biol. Chem.* 284 (2009) 8073–8082.
- [98] H.G. Palmer, M. Sanchez-Carbayo, P. Ordóñez-Moran, M.J. Larriba, C. Cordon-Cardo, A. Munoz, Genetic signatures of differentiation induced by 1 α ,25-dihydroxyvitamin D₃ in human colon cancer cells, *Cancer Res.* 63 (2003) 7799–7806.
- [99] S. Swami, N. Raghavachari, U.R. Muller, Y.P. Bao, D. Feldman, Vitamin D growth inhibition of breast cancer cells: gene expression patterns assessed by cDNA microarray, *Breast Cancer Res. Treat.* 80 (2003) 49–62.
- [100] R.J. Wood, L. Tchack, G. Angelo, R.E. Pratt, L.A. Sonna, DNA microarray analysis of vitamin D-induced gene expression in a human colon carcinoma cell line, *Physiol. Genomics* 17 (2004) 122–129.
- [101] Z. Wang, M. Gerstein, M. Snyder, RNA-Seq: a revolutionary tool for transcriptomics, *Nat. Rev. Genet.* 10 (2009) 57–63.
- [102] G. Ferrer-Mayorga, N. Niell, R. Cantero, J.M. Gonzalez-Sancho, L. Del Peso, A. Munoz, M.J. Larriba, Vitamin D and Wnt3A have additive and partially overlapping modulatory effects on gene expression and phenotype in human colon fibroblasts, *Sci. Rep.* 9 (2019) 8085.
- [103] M.S. Kim, R. Fujiki, A. Murayama, H. Kitagawa, K. Yamaoka, Y. Yamamoto, M. Mihara, K. Takeyama, S. Kato, 1 α ,25(OH)₂D₃-induced transrepression by vitamin D receptor through E-box-type elements in the human parathyroid hormone gene promoter, *Mol. Endocrinol.* 21 (2007) 334–342.
- [104] M.M. Turunen, T.W. Dunlop, C. Carlberg, S. Väisänen, Selective use of multiple vitamin D response elements underlies the 1 α ,25-dihydroxyvitamin D₃-mediated negative regulation of the human CYP27B1 gene, *Nucleic Acids Res.* 35 (2007) 2734–2747.
- [105] R.F. Chun, P.T. Liu, R.L. Modlin, J.S. Adams, M. Hewison, Impact of vitamin D on immune function: lessons learned from genome-wide analysis, *Front. Physiol.* 5 (2014) 151.
- [106] M. Medrano, E. Carrillo-Cruz, I. Montero, J.A. Perez-Simon, Vitamin D: effect on haematopoiesis and immune system and clinical applications, *Int. J. Mol. Sci.* 19 (2018).
- [107] M. Lu, B.J. McComish, K.P. Burdon, B.V. Taylor, H. Körner, The association between vitamin D and multiple sclerosis risk: 1,25(OH)₂D₃ induces super-enhancers bound by VDR, *Front. Immunol.* 10 (2019) 488.
- [108] W. Dankers, E.M. Colin, J.P. van Hamburg, E. Lubberts, Vitamin D in autoimmunity: molecular mechanisms and therapeutic potential, *Front. Immunol.* 7 (2016) 697.
- [109] O. Koivisto, A. Hanel, C. Carlberg, Key vitamin D target genes with functions in the immune system, *Nutrients* 12 (2020).
- [110] A.F. Gombart, The vitamin D-antimicrobial peptide pathway and its role in protection against infection, *Future Microbiol.* 4 (2009) 1151–1165.
- [111] I. Zanoni, F. Granucci, Role of CD14 in host protection against infections and in metabolism regulation, *Front. Cell. Infect. Microbiol.* 3 (2013) 32.
- [112] I. Zanoni, Y. Tan, M. Di Gioia, J.R. Springstead, J.C. Kagan, By capturing inflammatory lipids released from dying cells, the receptor CD14 induces inflammasome-dependent phagocyte hyperactivation, *Immunity* 47 (2017) 697–709 e3.
- [113] S. Liang, J. Cai, Y. Li, R. Yang, 1,25Dihydroxy Vitamin D3 induces macrophage polarization to M2 by upregulating Tcell Igmuc3 expression, *Mol. Med. Rep.* 19 (2019) 3707–3713.
- [114] M. Hewison, Vitamin D and innate and adaptive immunity, *Vitam. Horm.* 86 (2011) 23–62.
- [115] M. Ardesia, G. Ferlazzo, W. Fries, Vitamin D and inflammatory bowel disease, *Biomed Res. Int.* 2015 (2015) 470805.
- [116] S. Chetcuti Zammit, P. Ellul, G. Girardin, D. Valpiani, K.R. Nielsen, J. Olsen, A. Goldis, D. Lazar, O. Shonova, M. Novakova, S. Sebastian, E. Whitehead, A. Carmona, S. Martinez-Cadilla, J.F. Dahlerup, A.L.H. Kievit, N. Thorsgaard, K.H. Katsanos, D.K. Christodoulou, F. Magro, R. Salupere, N. Pedersen, J. Kjeldsen, K. Carlsen, K. Ioannis, D. Bergemalm, J. Halfvarson, D. Duricova, M. Bortlik, P. Collin, P. Oksanen, G. Kiudelis, L. Kupcinskas, K. Kudsk, V. Andersen, C. O'Morain, Y. Bailey, S. Doron, O. Shmuel, S. Almer, N. Arebi, R. Misra, S. Cukovic-Cavka, M. Brinar, P. Munkholm, Z. Vegh, J. Burisch, Vitamin D

- deficiency in a European inflammatory bowel disease inception cohort: an Epi-IBD study, *Eur. J. Gastroenterol. Hepatol.* 30 (2018) 1297–1303.
- [117] C.N. Bernstein, F. Shanahan, Disorders of a modern lifestyle: reconciling the epidemiology of inflammatory bowel diseases, *Gut* 57 (2008) 1185–1191.
- [118] H.S. de Souza, C. Fiocchi, Immunopathogenesis of IBD: current state of the art, *Nat. Rev. Gastroenterol. Hepatol.* 13 (2016) 13–27.
- [119] J. Fletcher, S.C. Cooper, S. Ghosh, M. Hewison, The role of vitamin D in inflammatory bowel disease: mechanism to management, *Nutrients* 11 (2019).
- [120] M.T. Cantorna, Vitamin D and its role in immunology: multiple sclerosis, and inflammatory bowel disease, *Prog. Biophys. Mol. Biol.* 92 (2006) 60–64.
- [121] N. Liu, L. Nguyen, R.F. Chun, V. Lagishetty, S. Ren, S. Wu, B. Hollis, H.F. DeLuca, J.S. Adams, M. Hewison, Altered endocrine and autocrine metabolism of vitamin D in a mouse model of gastrointestinal inflammation, *Endocrinology* 149 (2008) 4799–4808.
- [122] M. Froicu, V. Weaver, T.A. Wynn, M.A. McDowell, J.E. Welsh, M.T. Cantorna, A crucial role for the vitamin D receptor in experimental inflammatory bowel diseases, *Mol. Endocrinol.* 17 (2003) 2386–2392.
- [123] M.T. Cantorna, C. Munsick, C. Bemiss, B.D. Mahon, 1,25-Dihydroxycholecalciferol prevents and ameliorates symptoms of experimental murine inflammatory bowel disease, *J. Nutr.* 130 (2000) 2648–2652.
- [124] A.N. Ananthkrishnan, S.C. Cheng, T. Cai, A. Cagan, V.S. Gainer, P. Szolovits, S.Y. Shaw, S. Churchill, E.W. Karlson, S.N. Murphy, I. Kohane, K.P. Liao, Association between reduced plasma 25-hydroxy vitamin D and increased risk of cancer in patients with inflammatory bowel diseases, *Clin. Gastroenterol. Hepatol.* 12 (2014) 821–827.
- [125] A.K. Coussens, R.J. Wilkinson, Y. Hanifa, V. Nikolayevskyy, P.T. Elkington, K. Islam, P.M. Timms, T.R. Venton, G.H. Bothamley, G.E. Packe, M. Darmalingam, R.N. Davidson, H.J. Milburn, L.V. Baker, R.D. Barker, C.A. Mein, L. Bhaw-Rosun, R. Nuamah, D.B. Young, F.A. Drobniowski, C.J. Griffiths, A.R. Martineau, Vitamin D accelerates resolution of inflammatory responses during tuberculosis treatment, *Proc. Natl. Acad. Sci. U. S. A.* 109 (2012) 15449–15454.
- [126] S. Scolletta, M. Colletti, L. Di Luigi, C. Crescioli, Vitamin D receptor agonists target CXCL10: new therapeutic tools for resolution of inflammation, *Mediators Inflamm.* 2013 (2013) 876319.
- [127] S.M. Barbalho, R.A. Goulart, G. Batista, Vitamin A and inflammatory bowel diseases: from cellular studies and animal models to human disease, *Expert Rev. Gastroenterol. Hepatol.* 13 (2019) 25–35.
- [128] P. Protiva, S. Pendyala, C. Nelson, L.H. Augenlicht, M. Lipkin, P.R. Holt, Calcium and 1,25-dihydroxyvitamin D₃ modulate genes of immune and inflammatory pathways in the human colon: a human crossover trial, *Am. J. Clin. Nutr.* 103 (2016) 1224–1231.
- [129] P.H. Hart, S. Gorman, J.J. Finlay-Jones, Modulation of the immune system by UV radiation: more than just the effects of vitamin D? *Nat. Rev. Immunol.* 11 (2011) 584–596.
- [130] R. Sever, J.S. Brugge, Signal transduction in cancer, *Cold Spring Harb. Perspect. Med.* 5 (2015).
- [131] D. Balomenos, J. Martin-Caballero, M.I. Garcia, I. Prieto, J.M. Flores, M. Serrano, A.C. Martinez, The cell cycle inhibitor p21 controls T-cell proliferation and sex-linked lupus development, *Nat. Med.* 6 (2000) 171–176.
- [132] M.H. Sherman, R.T. Yu, D.D. Engle, N. Ding, A.R. Atkins, H. Tiriak, E.A. Collisson, F. Connor, T. Van Dyke, S. Kozlov, P. Martin, T.W. Tseng, D.W. Dawson, T.R. Donahue, A. Masamune, T. Shimosegawa, M.V. Apte, J.S. Wilson, B. Ng, S.L. Lau, J.E. Gunton, G.M. Wahl, T. Hunter, J.A. Drebin, P.J. O'Dwyer, C. Liddle, D.A. Tuveson, M. Downes, R.M. Evans, Vitamin D receptor-mediated stromal reprogramming suppresses pancreatitis and enhances pancreatic cancer therapy, *Cell* 159 (2014) 80–93.
- [133] X. Wu, W. Hu, L. Lu, Y. Zhao, Y. Zhou, Z. Xiao, L. Zhang, H. Zhang, X. Li, W. Li, S. Wang, C.H. Cho, J. Shen, M. Li, Repurposing vitamin D for treatment of human malignancies via targeting tumor microenvironment, *Acta Pharm. Sin. B* 9 (2019) 203–219.
- [134] J.L. Kelly, G. Salles, B. Goldman, R.I. Fisher, P. Brice, O. Casasnovas, D.G. Maloney, P. Soubeyran, L. Rimsza, C. Haioun, L. Xerri, M. LeBlanc, H. Tilly, J.W. Friedberg, Low serum vitamin D levels are associated with inferior survival in follicular lymphoma: a prospective evaluation in SWOG and LYSA studies, *J. Clin. Oncol.* 33 (2015) 1482–1490.
- [135] S.B. Zeichner, T. Koru-Sengul, N. Shah, Q. Liu, N.J. Markward, A.J. Montero, S. Gluck, O. Silva, E.R. Ahn, Improved clinical outcomes associated with vitamin D supplementation during adjuvant chemotherapy in patients with HER2⁺ non-metastatic breast cancer, *Clin. Breast Cancer* 15 (2015) e1–11.
- [136] L. Martinez-Lostao, A. Anel, J. Pardo, How do cytotoxic lymphocytes kill cancer cells? *Clin. Cancer Res.* 21 (2015) 5047–5056.
- [137] E. Karkeni, S.O. Morin, B. Bou Tayeh, A. Goubard, E. Josselin, R. Castellano, C. Fauriat, G. Guittard, D. Olive, J.A. Nunes, Vitamin D controls tumor growth and CD8⁺ T cell infiltration in breast cancer, *Front. Immunol.* 10 (2019) 1307.
- [138] G. Ferrer-Mayorga, M.J. Larriba, P. Crespo, A. Munoz, Mechanisms of action of vitamin D in colon cancer, *J. Steroid Biochem. Mol. Biol.* 185 (2019) 1–6.
- [139] N. Cancer Genome Atlas, Comprehensive molecular portraits of human breast tumours, *Nature* 490 (2012) 61–70.
- [140] R. Yaeger, W.K. Chatila, M.D. Lipsyc, J.F. Hechtman, A. Cercek, F. Sanchez-Vega, G. Jayakumar, S. Middha, A. Zehir, M.T.A. Donoghue, D. You, A. Viale, N. Kemeny, N.H. Segal, Z.K. Stadler, A.M. Varghese, R. Kundra, J. Gao, A. Syed, D.M. Hyman, E. Vakiani, N. Rosen, B.S. Taylor, M. Ladanyi, M.F. Berger, D.B. Solit, J. Shia, L. Saltz, N. Schultz, Clinical sequencing defines the genomic landscape of metastatic colorectal cancer, *Cancer Cell* 33 (2018) 125–136 e3.
- [141] H.G. Palmer, J.M. Gonzalez-Sancho, J. Espada, M.T. Berciano, I. Puig, J. Baulida, M. Quintanilla, A. Cano, A.G. de Herrerros, M. Lafarga, A. Munoz, Vitamin D₃ promotes the differentiation of colon carcinoma cells by the induction of E-cadherin and the inhibition of beta-catenin signaling, *J. Cell Biol.* 154 (2001) 369–387.
- [142] O. Aguilera, C. Pena, J.M. Garcia, M.J. Larriba, P. Ordóñez-Moran, D. Navarro, A. Barbachano, I. Lopez de Silanes, E. Ballestar, M.F. Fraga, M. Esteller, C. Gamallo, F. Bonilla, J.M. Gonzalez-Sancho, A. Munoz, The Wnt antagonist DICKKOPF-1 gene is induced by 1 α ,25-dihydroxyvitamin D₃ associated to the differentiation of human colon cancer cells, *Carcinogenesis* 28 (2007) 1877–1884.
- [143] M.J. Larriba, J.M. Gonzalez-Sancho, A. Barbachano, N. Niell, G. Ferrer-Mayorga, A. Munoz, Vitamin D is a multilevel repressor of Wnt/b-catenin signaling in cancer cells, *Cancers (Basel)* 5 (2013) 1242–1260.
- [144] S. Toropainen, S. Väisänen, S. Heikkinen, C. Carlberg, The down-regulation of the human MYC gene by the nuclear hormone 1 α ,25-dihydroxyvitamin D₃ is associated with cycling of corepressors and histone deacetylases, *J. Mol. Biol.* 400 (2010) 284–294.
- [145] R. Salehi-Tabar, L. Nguyen-Yamamoto, L.E. Tavera-Mendoza, T. Quail, V. Dimitrov, B.S. An, L. Glass, D. Goltzman, J.H. White, Vitamin D receptor as a master regulator of the c-MYC/MXD1 network, *Proc. Natl. Acad. Sci. U. S. A.* 109 (2012) 18827–18832.
- [146] R. Salehi-Tabar, B. Memari, H. Wong, V. Dimitrov, N. Rochel, J.H. White, The tumor suppressor FBW7 and the vitamin D receptor are mutual cofactors in protein turnover and transcriptional regulation, *Mol. Cancer Res.* 17 (2019) 709–719.
- [147] W.M. Tong, H. Hofer, A. Ellinger, M. Peterlik, H.S. Cross, Mechanism of anti-mitogenic action of vitamin D in human colon carcinoma cells: relevance for suppression of epidermal growth factor-stimulated cell growth, *Oncol. Res.* 11 (1999) 77–84.
- [148] A. Barbachano, A. Fernandez-Barral, F. Pereira, M.F. Segura, P. Ordóñez-Moran, E. Carrillo-de Santa Pau, J.M. Gonzalez-Sancho, D. Hanniford, N. Martinez, A. Costales-Carrera, F.X. Real, H.G. Palmer, J.M. Rojas, E. Hernandez, A. Munoz, SPROUTY-2 represses the epithelial phenotype of colon carcinoma cells via up-regulation of ZEB1 mediated by ETS1 and miR-200/miR-150, *Oncogene* 35 (2016) 2991–3003.
- [149] A. Barbachano, P. Ordóñez-Moran, J.M. Garcia, A. Sanchez, F. Pereira, M.J. Larriba, N. Martinez, J. Hernandez, S. Landolfi, F. Bonilla, H.G. Palmer, J.M. Rojas, A. Munoz, SPROUTY-2 and E-cadherin regulate reciprocally and dictate colon cancer cell tumorigenicity, *Oncogene* 29 (2010) 4800–4813.
- [150] N.I. Fernandez-Garcia, H.G. Palmer, M. Garcia, A. Gonzalez-Martin, M. del Rio, D. Baretino, O. Volpert, A. Munoz, B. Jimenez, 1 α ,25-Dihydroxyvitamin D₃ regulates the expression of Id1 and Id2 genes and the angiogenic phenotype of human colon carcinoma cells, *Oncogene* 24 (2005) 6533–6544.
- [151] M. Ben-Shoshan, S. Amir, D.T. Dang, L.H. Dang, Y. Weisman, N.J. Mabeesh, 1 α ,25-dihydroxyvitamin D₃ (Calcitriol) inhibits hypoxia-inducible factor-1/vascular endothelial growth factor pathway in human cancer cells, *Mol. Cancer Ther.* 6 (2007) 1433–1439.
- [152] F. Pereira, A. Barbachano, P.K. Singh, M.J. Campbell, A. Munoz, M.J. Larriba, Vitamin D has wide regulatory effects on histone demethylase genes, *Cell Cycle* 11 (2012) 1081–1089.
- [153] G. Ferrer-Mayorga, S. Alvarez-Diaz, N. Valle, J. De Las Rivas, M. Mendes, R. Barderas, F. Canals, O. Tapia, J.I. Casal, M. Lafarga, A. Munoz, Cystatin D locates in the nucleus at sites of active transcription and modulates gene and protein expression, *J. Biol. Chem.* 290 (2015) 26533–26548.
- [154] S. Alvarez-Diaz, N. Valle, J.M. Garcia, C. Pena, J.M. Freije, V. Quesada, A. Astudillo, F. Bonilla, C. Lopez-Otin, A. Munoz, Cystatin D is a candidate tumor suppressor gene induced by vitamin D in human colon cancer cells, *J. Clin. Invest.* 119 (2009) 2343–2358.
- [155] S. Alvarez-Diaz, M.J. Larriba, C. Lopez-Otin, A. Munoz, Vitamin D: proteases, protease inhibitors and cancer, *Cell Cycle* 9 (2010) 32–37.
- [156] S. Alvarez-Diaz, N. Valle, G. Ferrer-Mayorga, L. Lombardia, M. Herrera, O. Dominguez, M.F. Segura, F. Bonilla, E. Hernandez, A. Munoz, MicroRNA-22 is induced by vitamin D and contributes to its antiproliferative, antimigratory and gene regulatory effects in colon cancer cells, *Hum. Mol. Genet.* 21 (2012) 2157–2165.
- [157] P. Ordóñez-Moran, M.J. Larriba, H.G. Palmer, R.A. Valero, A. Barbachano, M. Dunach, A.G. de Herrerros, C. Villalobos, M.T. Berciano, M. Lafarga, A. Munoz, RhoA-ROCK and p38MAPK-MSK1 mediate vitamin D effects on gene expression, phenotype, and Wnt pathway in colon cancer cells, *J. Cell Biol.* 183 (2008) 697–710.
- [158] H.G. Palmer, M.J. Larriba, J.M. Garcia, P. Ordóñez-Moran, C. Pena, S. Peiro, I. Puig, R. Rodriguez, R. De La Fuente, A. Bernad, M. Pollan, F. Bonilla, C. Gamallo, A.G. de Herrerros, A. Munoz, The transcription factor SNAIL represses vitamin D receptor expression and responsiveness in human colon cancer, *Nat. Med.* 10 (2004) 917–919.
- [159] M.J. Larriba, E. Martin-Villar, J.M. Garcia, F. Pereira, C. Pena, A.G. de Herrerros, F. Bonilla, A. Munoz, Snail2 cooperates with Snail1 in the repression of vitamin D receptor in colon cancer, *Carcinogenesis* 30 (2009) 1459–1468.
- [160] A. Duran, E.D. Hernandez, M. Reina-Campos, E.A. Castilla, S. Subramaniam, S. Raghunandan, L.R. Roberts, T. Kisseleva, M. Karin, M.T. Diaz-Meco, J. Moscat, p62/SQSTM1 by binding to vitamin D receptor inhibits hepatic stellate cell activity, fibrosis, and liver cancer, *Cancer Cell* 30 (2016) 595–609.
- [161] C. Tomasetti, B. Vogelstein, On the slope of the regression between stem cell divisions and cancer risk, and the lack of correlation between stem cell divisions and environmental factors-associated cancer risk, *PLoS One* 12 (2017) e0175535.
- [162] K. Peregrina, M. Houston, C. Daroqui, E. Dhima, R.S. Sellers, L.H. Augenlicht, Vitamin D is a determinant of mouse intestinal Lgr5 stem cell functions, *Carcinogenesis* 36 (2015) 25–31.
- [163] L.H. Augenlicht, Environmental impact on intestinal stem cell functions in

- mucosal homeostasis and tumorigenesis, *J. Cell. Biochem.* 118 (2017) 943–952.
- [164] W. Li, S.E. Zimmerman, K. Peregrina, M. Houston, J. Mayoral, J. Zhang, S. Maqbool, Z. Zhang, Y. Cai, K. Ye, L.H. Augenlicht, The nutritional environment determines which and how intestinal stem cells contribute to homeostasis and tumorigenesis, *Carcinogenesis* 40 (2019) 937–946.
- [165] W.B. Grant, Review of recent advances in understanding the role of vitamin D in reducing cancer risk: breast, colorectal, prostate, and overall cancer, *Anticancer Res.* 40 (2020) 491–499.
- [166] N. Estebanez, I. Gomez-Acebo, C. Palazuelos, J. Llorca, T. Dierssen-Sotos, Vitamin D exposure and risk of breast cancer: a meta-analysis, *Sci. Rep.* 8 (2018) 9039.
- [167] V. Lope, A. Castello, A. Mena-Bravo, P. Amiano, N. Aragones, T. Fernandez-Villa, M. Guevara, T. Dierssen-Sotos, G. Fernandez-Tardon, G. Castano-Vinyals, R. Marcos-Gragera, V. Moreno, D. Salas-Trejo, M. Diaz-Santos, M. Oribe, I. Romieu, M. Kogevinas, F. Priego-Capote, B. Perez-Gomez, M. Pollan, Serum 25-hydroxyvitamin D and breast cancer risk by pathological subtype (MCC-Spain), *J. Steroid Biochem. Mol. Biol.* 182 (2018) 4–13.
- [168] B. Qin, B. Xu, N. Ji, S. Yao, K. Pawlish, A.A.M. Llanos, Y. Lin, K. Demissie, C.B. Ambrosone, C.C. Hong, E.V. Bandera, Intake of vitamin D and calcium, sun exposure, and risk of breast cancer subtypes among black women, *Am. J. Clin. Nutr.* 111 (2020) 396–405.
- [169] M. Soljic, I. Mrklic, S. Tomic, T. Omrcen, N. Sutalo, M. Bevanda, E. Vrdoljak, Prognostic value of vitamin D receptor and insulin-like growth factor receptor 1 expression in triple-negative breast cancer, *J. Clin. Pathol.* 71 (2018) 34–39.
- [170] J. Welsh, Vitamin D and breast cancer: past and present, *J. Steroid Biochem. Mol. Biol.* 177 (2018) 15–20.
- [171] M. Simboli-Campbell, C.J. Narvaez, K. van Weelden, M. Tenniswood, J. Welsh, Comparative effects of 1,25(OH)₂D₃ and EB1089 on cell cycle kinetics and apoptosis in MCF-7 breast cancer cells, *Breast Cancer Res. Treat.* 42 (1996) 31–41.
- [172] J. Welsh, Induction of apoptosis in breast cancer cells in response to vitamin D and antiestrogens, *Biochem. Cell Biol.* 72 (1994) 537–545.
- [173] S.Y. James, A.G. Mackay, K.W. Colston, Effects of 1,25 dihydroxyvitamin D₃ and its analogues on induction of apoptosis in breast cancer cells, *J. Steroid Biochem. Mol. Biol.* 58 (1996) 395–401.
- [174] J.M. Gonzalez-Sancho, M. Alvarez-Dolado, A. Munoz, 1,25-Dihydroxyvitamin D₃ inhibits tenascin-C expression in mammary epithelial cells, *FEBS Lett.* 426 (1998) 225–228.
- [175] N. Pendas-Franco, J.M. Gonzalez-Sancho, Y. Suarez, O. Aguilera, A. Steinmeyer, C. Gamallo, M.T. Berciano, M. Lafarga, A. Munoz, Vitamin D regulates the phenotype of human breast cancer cells, *Differentiation* 75 (2007) 193–207.
- [176] N. Lopes, J. Paredes, J.L. Costa, B. Ylstra, F. Schmitt, Vitamin D and the mammary gland: a review on its role in normal development and breast cancer, *Breast Cancer Res.* 14 (2012) 211.
- [177] A.V. Krishnan, S. Swami, D. Feldman, Vitamin D and breast cancer: inhibition of estrogen synthesis and signaling, *J. Steroid Biochem. Mol. Biol.* 121 (2010) 343–348.
- [178] A. Aggarwal, D. Feldman, B.J. Feldman, Identification of tumor-autonomous and indirect effects of vitamin D action that inhibit breast cancer growth and tumor progression, *J. Steroid Biochem. Mol. Biol.* 177 (2018) 155–158.
- [179] Y. Jeong, S. Swami, A.V. Krishnan, J.D. Williams, S. Martin, R.L. Horst, M.A. Albertelli, B.J. Feldman, D. Feldman, M. Diehn, Inhibition of mouse breast tumor-initiating cells by calcitriol and dietary vitamin D, *Mol. Cancer Ther.* 14 (2015) 1951–1961.
- [180] N.L. Shan, J. Wahler, H.J. Lee, M.J. Bak, S.D. Gupta, H. Maehr, N. Suh, Vitamin D compounds inhibit cancer stem-like cells and induce differentiation in triple negative breast cancer, *J. Steroid Biochem. Mol. Biol.* 173 (2017) 122–129.
- [181] Z.Y. Song, Q. Yao, Z. Zhuo, Z. Ma, G. Chen, Circulating vitamin D level and mortality in prostate cancer patients: a dose-response meta-analysis, *Endocr. Connect.* 7 (2018) R294–R303.
- [182] S. Shahvazi, S. Soltani, S.M. Ahmadi, R.J. de Souza, A. Salehi-Abargouei, The effect of vitamin D supplementation on prostate cancer: a systematic review and meta-analysis of clinical trials, *Horm. Metab. Res.* 51 (2019) 11–21.
- [183] D.L. Trump, J.B. Aragon-Ching, Vitamin D in prostate cancer, *Asian J. Androl.* 20 (2018) 244–252.
- [184] Q. Wang, Y. He, Y. Shen, Q. Zhang, D. Chen, C. Zuo, J. Qin, H. Wang, J. Wang, Y. Yu, Vitamin D inhibits COX-2 expression and inflammatory response by targeting thioesterase superfamily member 4, *J. Biol. Chem.* 289 (2014) 11681–11694.
- [185] P.L. Kovalenko, Z. Zhang, M. Cui, S.K. Clinton, J.C. Fleet, 1,25 dihydroxyvitamin D-mediated orchestration of anticancer, transcript-level effects in the immortalized, non-transformed prostate epithelial cell line, RWPE1, *BMC Genomics* 11 (2010) 26.
- [186] A.A. Ajibade, J.S. Kirk, E. Karasik, B. Gillard, M.T. Moser, C.S. Johnson, D.L. Trump, B.A. Foster, Early growth inhibition is followed by increased metastatic disease with vitamin D (calcitriol) treatment in the TRAMP model of prostate cancer, *PLoS One* 9 (2014) e89555.
- [187] W. Wang, G. Li, X. He, J. Gao, R. Wang, Y. Wang, W. Zhao, Serum 25-hydroxyvitamin D levels and prognosis in hematological malignancies: a systematic review and meta-analysis, *Cell. Physiol. Biochem.* 35 (2015) 1999–2005.
- [188] B. Lauter, I.G. Schmidt-Wolf, Prevalence, supplementation, and impact of vitamin D deficiency in multiple myeloma patients, *Cancer Invest.* 33 (2015) 505–509.
- [189] S.M.S. Pezeshki, A.A. Asnafi, A. Khosravi, M. Shahjahani, S. Azizidoost, S. Shahrabi, Vitamin D and its receptor polymorphisms: new possible prognostic biomarkers in leukemias, *Oncol. Rev.* 12 (2018) 366.
- [190] S. Bhattacharya, N. Verma, A. Kumar, Prevalence of vitamin D deficiency in childhood acute lymphoblastic leukemia and its association with adverse outcomes during induction phase of treatment, *Nutr. Cancer* (2020) in press.
- [191] P.M. Kulling, K.C. Olson, T.L. Olson, D.J. Feith, T.P. Loughran Jr., Vitamin D in hematological disorders and malignancies, *Eur. J. Haematol.* 98 (2017) 187–197.
- [192] K.C. Olson, P.M. Kulling Larkin, R. Signorelli, C.E. Hamele, T.L. Olson, M.R. Conaway, D.J. Feith, T.P. Loughran Jr., Vitamin D pathway activation selectively deactivates signal transducer and activator of transcription (STAT) proteins and inflammatory cytokine production in natural killer leukemic large granular lymphocytes, *Cytokine* 111 (2018) 551–562.
- [193] H. Guo, S.Y. Lin, W.X. Ren, Q. Lei, Z.C. Chen, L. Zhang, Q.B. Li, Enhanced response of acute myelocytic leukemia cells to low-dose cytarabine by 1,25-dihydroxyvitamin D₃, *Curr. Issues Pharm. Med. Sci. Pract.* 38 (2018) 35–42.
- [194] H.P. Koefler, T. Amatruda, N. Ikekawa, Y. Kobayashi, H.F. DeLuca, Induction of macrophage differentiation of human normal and leukemic myeloid stem cells by 1,25-dihydroxyvitamin D₃ and its fluorinated analogues, *Cancer Res.* 44 (1984) 5624–5628.
- [195] A. Marchwicka, E. Marcinkowska, Regulation of expression of CEBP genes by variably expressed vitamin D receptor and retinoic acid receptor alpha in human acute myeloid leukemia cell lines, *Int. J. Mol. Sci.* 19 (2018).
- [196] M. Liu, M.-H. Lee, M. Cohen, M. Bommakanti, L.P. Freedman, Transcriptional activation of the Cdk inhibitor p21 by vitamin D₃ leads to the induced differentiation of the myelomonocytic cell line U937, *Genes Dev.* 10 (1996) 142–153.
- [197] J. Ryyänen, C. Carlberg, Primary 1,25-dihydroxyvitamin D₃ response of the interleukin 8 gene cluster in human monocyte- and macrophage-like cells, *PLoS One* 8 (2013) e78170.
- [198] J. Ros-Soto, C. Anthias, A. Madrigal, J.A. Snowden, Vitamin D: is it important in haematopoietic stem cell transplantation? A review, *Bone Marrow Transplant.* 54 (2019) 810–820.
- [199] A. Radujkovic, L. Kordelas, J. Krzykalla, D.W. Beelen, A. Benner, N. Lehners, K. Schmidt, P. Dreger, T. Luft, Pretransplant vitamin D deficiency is associated with higher relapse rates in patients allografted for myeloid malignancies, *J. Clin. Oncol.* 35 (2017) 3143–3152.
- [200] E. Paubelle, F. Zylbersztejn, T.T. Maciel, C. Carvalho, A. Mupo, M. Cheok, L. Lieben, P. Stjobert, J. Decroocq, A. Yokoyama, V. Asnafi, E. Macintyre, J. Tamburini, V. Bardet, S. Castaigne, C. Preudhomme, H. Dombret, G. Carmeliet, D. Bouscary, Y.Z. Ginzburg, H. de The, M. Benhamou, R.C. Monteiro, G.S. Vassiliou, O. Hermine, I.C. Moura, Vitamin D receptor controls cell stemness in acute myeloid leukemia and in normal bone marrow, *Cell Rep.* 30 (2020) 739–754 e4.
- [201] H. Thorvaldsdottir, J.T. Robinson, J.P. Mesirov, Integrative Genomics Viewer (IGV): high-performance genomics data visualization and exploration, *Brief Bioinform* 14 (2013) 178–192.