Vitamin D and the vitamin D receptor (VDR) have been shown to be important regulators of the immune system. In particular, vitamin D and VDR deficiency exacerbates experimental autoimmune diseases such as inflammatory bowel disease (IBD). IBD develops due to an immune-mediated attack by pathogenic T-cells that overproduce IL-17 and IFN-γ and a few regulatory cells. VDR knockout mice have twice as many T-cells making IL-17 and IFN-γ than wild-type mice. In addition, vitamin D and the VDR are required for normal numbers of regulatory T-cells (iNKT and CD8αα) that have been shown to suppress experimental IBD. In the absence of vitamin D and the VDR, autoimmunity occurs in the gastrointestinal tract due to increased numbers of IL-17 and IFN-γ secreting T-cells and a concomitant reduction in regulatory T-cells.

Vitamin D: Regulatory T cells: Inflammatory bowel disease: Multiple sclerosis

The incidence of immune-mediated diseases such as multiple sclerosis and inflammatory bowel disease (IBD) has increased in developed countries over the last 50 years. To explain the increased incidence of immune-mediated diseases as well as the geographical restriction of these diseases to the developed world, the hygiene hypothesis has been put forward. The hygiene hypothesis states that reduced exposure to microbial components results in immune dysregulation and T-cell responses that drive immune-mediated disease. We propose that other factors in the environment in addition to the hygiene hypothesis are important in the development of the immune response leading to multiple sclerosis and IBD. We propose that decreased outdoor activity, increased pollution and diets that lack adequate vitamin D have combined to create large fluctuations in vitamin D status in developed countries and especially in populations that experience winter(1,2). The vitamin D hypothesis proposes that vitamin D regulates the development and function of the immune system and that early childhood and prenatal changes in vitamin D status affect the resultant immune response and the development of autoimmune diseases(3,4). Here we will describe the current understanding of the mechanisms by which vitamin D regulates experimental autoimmunity.

Vitamin D

A major source of vitamin D results from its manufacture via a photolysis reaction in the skin, and vitamin D available from sunlight exposure is significantly less in northern climates and especially low during the winter(5,6). In addition, dietary intake of vitamin D is problematic since there are few foods that are naturally rich in vitamin D. There is mounting evidence for a link between vitamin D availability either from sunshine or from diet and the prevalence of autoimmune diseases(7). The use of supplemental vitamin D (500–600 IU) is associated with a 40% reduction in the risk of developing multiple sclerosis(8). In addition, vitamin D deficiency is common in patients with autoimmune diseases(9). The amount of vitamin D in the environment (food, sun or supplements) might influence the development and function of specific arms of the immune system. With our present lifestyles that feature

Abbreviations: EAE, experimental autoimmune encephalomyelitis; IEL, intraepithelial lymphocytes; iNKT, invariant NKT cell; αGalCer, α-galactoceramide; IBD, inflammatory bowel disease; KO, knockout; TCR, T-cell receptor; VDR, vitamin D receptor; WT, wild-type.

Corresponding author: Dr Margherita T. Cantorna, fax 814-863-6140, email mxc69@psu.edu
Vitamin D and immune regulation

The function of vitamin D is regulation of Ca homeostasis and thus bone formation and resorption. The discovery of the vitamin D receptor (VDR) in cells of the immune system and the presence of the 1α-25(OH) vitamin D3 hydroxylase in dendritic cells and macrophages suggest that locally produced 1,25(OH)2D3 has regulatory autocrine and paracrine properties at the site of inflammation. Synthesis of active vitamin D requires the 1α hydroxylase, which catalyses the conversion of 25(OH)D3 to 1,25(OH)2D3. The actions of 1,25(OH)2D3 are mediated by its binding to the VDR, which acts as a transcription factor to modulate the expression of genes in a tissue-specific manner. The VDR is a member of the steroid/hormone superfamily of nuclear transcription factors and is constitutively expressed in a variety of immune cells. Resting T-cells express low levels of VDR, which are upregulated following activation. The active form of vitamin D (1,25(OH)2D3) has been recognized as an immunosuppressive agent that ameliorates the pathogenesis of T helper 1-mediated autoimmune diseases including IBD and experimental autoimmune encephalomyelitis (EAE; a murine model of multiple sclerosis). Furthermore, vitamin D deficiency and VDR deficiency have been shown to exacerbate experimental IBD in three different mouse models. The increase in T regulatory cells caused by 1,25(OH)2D3 both in vitro and in vivo has been suggested as a mechanism underlying the ability of 1,25(OH)2D3 to suppress autoimmunity. In addition, genome-wide screening techniques suggest that VDR polymorphisms are associated with increased susceptibility to both Crohn’s disease and ulcerative colitis in human subjects.

Vitamin D and experimental inflammatory bowel disease

Mice lacking the VDR do not develop overt symptoms or present histological evidence of IBD even when they are housed in conventional facilities. However, increased expression of IL-1β and TNF-α in the colon of young (5 week old) and old (9 month old) VDR knockout (KO) mice when compared to age-matched wild-type (WT) mice suggests that VDR deficiency results in chronic and low-grade inflammation in the gastrointestinal tract. T-cells from VDR KO mice have been shown to exhibit a more pathogenic phenotype than WT T-cells. Specifically, VDR KO T-cells express an inflammatory phenotype, proliferate twice as much in a mixed lymphocyte reaction and transfer a more severe form of IBD than their WT counterparts.

In part the increased pathogenicity of the VDR KO T-cells was shown to be a result of increased IFN-γ and IL-17 (unpublished IL-17 results). VDR KO mice have heightened immune responses and inflammation in the colon, which suggest that the absence of the VDR predisposes to the development of IBD.

FoxP3+ T regulatory cells

CD4+ T-cells from VDR KO mice failed to suppress IBD, whereas WT CD4+ T-cells were effective in suppressing the same model of IBD. T regulatory cells that express the transcription factor FoxP3 and produce IL-10 are important for the maintenance of self-tolerance and the suppression of IBD. It has been shown that a combination of 1,25(OH)2D3 and dexamethasone induces IL-10-producing T regulatory cells in vitro. Furthermore, in vivo 1,25(OH)2D3 treatment of experimental autoimmune diabetes induces a population of T regulatory cells that correlates with protection of the mice from diabetes. The percentages of FoxP3+ T regulatory cells in the VDR KO and WT mice were determined. The numbers of T regulatory cells in the spleen, thymus or intraepithelial lymphocytes (IEL) of VDR KO and WT mice were not different. T regulatory cells were tested in vitro for functional suppression of naïve T-cell proliferation to CD3 antibodies. T regulatory cells from VDR KO mice were as effective as WT T regulatory cells in suppressing proliferation of both WT and VDR KO T-cells. T regulatory cells were sorted from VDR KO and WT mice and tested in vivo for suppression of IBD induced by WT naïve T-cell transfers to T- and B-cell-deficient Rag KO mice. Either WT or VDR KO T regulatory cells suppressed IBD development when they were transferred at the same time as the naïve T-cells. The T regulatory cells from VDR KO mice function to suppress proliferation in vitro and IBD in vivo. Therefore, it seems that expression of the VDR is not required for the development or function of T regulatory cells.

Invariant NKT-cells

NKT-cells are thought to be amongst the earliest producers of cytokines in an immune response and have been shown to influence a wide variety of different diseases. NKT-cells are narrowly defined as T-cells that express NK lineage receptors and an αβ T-cell receptor (TCR). The majority of NKT-cells express an invariant TCR (iNKT) and are responsive to a marine sponge sphingolipid, α-galactoceramide (αGalCer). NKT-cells play an important regulatory role in several models of autoimmunity, infection, cancer and atherosclerosis. Because NKT cell activation induces an early production of IL-4, NKT cell activation has been shown to delay the onset and reduce the symptoms of EAE and experimentally induced colitis. In addition, transgenic mice that overexpress NKT-cells are protected from the development of EAE.

To investigate whether vitamin D affects in vivo NKT cell function, VDR KO, WT and 1,25(OH)2D3-fed WT mice were injected with αGalCer. Feeding WT mice
1,25(OH)₂D₃ for 1 week prior to αGalCer injection increased IFN-γ and IL-4 production in the serum. VDR KO mice injected with αGalCer produced significantly less IFN-γ and IL-4 in the serum than both the WT and 1,25(OH)₂D₃-fed WT mice(31). The numbers of NKT-cells in the thymus, spleen and liver of WT and VDR KO mice were determined using CD1d-αGalCer tetramer staining. The percentages of iNKT-cells were significantly lower in VDR KO thymus, liver and spleen compared to WT mice(31).

iNKT-cells develop predominately in the thymus, with the final step in maturation (conversion to NK1.1 expression) occurring in both the thymus and peripheral lymphoid tissues. The majority of VDR KO iNKT-cells failed to express NK1.1 and therefore were not fully matured(31). To determine whether the residual VDR KO iNKT-cells are functionally different from WT iNKT-cells, cytokine production from iNKT-cells was assessed at the single-cell level by intracellular staining. Less than 3% of the iNKT-cells from the spleen of VDR KO mice made IL-4 and 25% made IFN-γ(31). Conversely, 15% of spleen-derived WT iNKT-cells produced IL-4 and 46% produced IFN-γ(31). VDR KO mice have fewer, less mature iNKT-cells and the residual iNKT-cells from VDR KO mice are defective for production of both IL-4 and IFN-γ.

CD8αα/T-cell receptor αβ intraepithelial lymphocytes

The gut contains a large number of T-cells and, unlike cells in the periphery, many of those T-cells express CD8αα either alone or in combination with CD4 or CD8αβ(32). Expression of CD8αα on T-cells decreases the sensitivity of those cells to antigen(32,33). The presence of CD8αα T-cells is thought to help maintain tolerance to the bacterial and food antigens that abound in the gastrointestinal tract. Studies with CD45.1 WT and CD45.2 VDR KO mice(31) demonstrated that CD8αα cells in the gut of VDR KO mice were made IFN-γ and IL-10(31). VDR KO T-cells repopulate the spleen but fail to home to the intestine.

Conclusions

Increased autoimmunity in VDR KO mice is a result of the increased pathogenicity of naïve T-cells and deficiency in two regulatory T-cell populations(23,31). The CD8αα T-cells are specific for the gut and maintain gastrointestinal homeostasis by inhibiting immune responses to gut antigens. The iNKT-cells are early cytokine producers that link the innate and adaptive immune responses. iNKT-cells have been shown to play a regulatory role in experimental autoimmunity including EAE and IBD. Conversely, the FoxP3+ regulatory cells do not require expression of the VDR for developing normally. Protective T-cells require expression of the VDR and vitamin D for developing and functioning normally. The effects of vitamin D on the immune system will then be most severe for diseases like EAE and IBD that are regulated by iNKT-cells and CD8αα T-cells.

Acknowledgements

The author declares no conflicts of interest. The work described in this paper was supported by the National Institutes of Health/National Institute of Diabetes and Digestive and Kidney Diseases (DK070781) and National Center for Complementary and Alternative Medicine and by the Office of Dietary Supplements (AT005378).

References


