Proceedings of the Nutrition Society (2015), **74**, 5–12 doi:10.1017/S0029665114001621
 First published online 10 December 2014

The Winter Meeting of the Nutrition Society was held at the Royal College of Surgeons, London on 11–12 December 2013

Conference on 'Diet, gut microbiology and human health'
Sir David Cuthbertson Medal Lecture

Vitamin D as a novel therapy in inflammatory bowel disease: new hope or false dawn?

Maria O'Sullivan

Department Clinical Medicine, Trinity College Dublin, Centre for Health Sciences, St James' Hospital, Dublin 8, Ireland

There is increasing scientific interest in the field of vitamin D research, moving the focus beyond bone health to other disease processes. Low circulating vitamin D levels have been reported as a risk factor for several pathophysiologically divergent diseases, including cancers, diabetes, CVD, multiple sclerosis and inflammatory diseases, including rheumatoid arthritis and inflammatory bowel disease (IBD). But, therein, remains the challenge: can any single nutrient contribute to multiple complex disease mechanisms and, ultimately, have therapeutic potential? The aim of this review is to critically evaluate several strands of scientific evidence surrounding vitamin D and inflammation, primarily focusing on IBD. Epidemiological studies suggest an increased incidence of IBD and rheumatoid arthritis in countries of more northern latitudes, mirroring sunlight patterns. A considerable body of evidence supports the anti-inflammatory effects of vitamin D, at least in animal models of IBD. Although it is accepted that suboptimal vitamin D status is common in IBD, some studies suggest that this associates with more severe disease. With regard to treatment, the data are only beginning to emerge from randomised controlled trials to suggest that people with IBD may remain in remission longer when treated with oral vitamin D. In conclusion, several strands of evidence suggest that vitamin D may modify the immune response in IBD. There is a continued need for large well-designed clinical trials and mechanistic studies to determine if, and how, this emerging promise translates into tangible clinical benefits for people with chronic debilitating diseases such as IBD.

Vitamin D: Inflammatory bowel disease: Autoimmune disease: Nutrition

Vitamin D and immunomodulation: the inflammatory bowel disease perspective

There is increasing scientific interest in the field of vitamin D research, moving the focus beyond traditional known roles in bone health to other disease processes. Maintaining adequate serum vitamin D levels has been associated with a reduced risk of several pathophysiologically divergent diseases, including cancers, diabetes, CVD, multiple sclerosis and inflammatory diseases such as rheumatoid arthritis and inflammatory bowel disease (IBD) [1]. But, therein, is the challenge: can any single nutrient contribute to multiple complex disease mechanisms and, ultimately, have potential to treat these diseases? Across a number of the autoimmune diseases, including rheumatoid arthritis, multiple sclerosis, asthma, systemic lupus erythematous and IBD, studies suggest that vitamin D status may be associated with initiation, progression or severity of these diseases[1–6].

In IBD, there is an established role for vitamin D in the prevention and treatment of osteoporosis, which is a known complication of this disease[7–9]. Indeed, there are clinical management guidelines for bone health[10], for example, that recommend vitamin D and calcium

Abbreviations: 25(OH)D, 25-hydroxyvitamin D; CD, Crohn's disease; CDAI, Crohn's disease activity index; CRP, C-reactive protein; IBD, inflammatory bowel disease; RCT, randomised controlled trial; UC, ulcerative colitis.

Corresponding author: Professor Maria O'Sullivan, email maria.osullivan@tcd.ie

supplementation for IBD patients undergoing treatment with corticosteroids. There is new interest, however, in vitamin D in IBD 'beyond bone' as a treatment for the core inflammatory disease. Growing evidence from epidemiological studies, animal models, cross-sectional studies and some intervention studies appear to support such a role[11–15]. The aim of this review is to critically evaluate several strands of scientific evidence surrounding vitamin D and inflammation in autoimmune diseases, primarily focusing on IBD and to understand how this translates to disease management.

IBD encompasses two conditions, Crohn's disease (CD) and a related condition, ulcerative colitis (UC). CD is a lifelong chronic relapsing and remitting inflammatory condition affecting any part of the gastrointestinal tract. Symptoms include diarrhoea, abdominal pain, fever and fatigue. The disease is named after Dr Burrill Crohn, who in 1932, along with his colleagues, published a landmark paper describing a condition now known as CD [16]. UC is a similar entity, but as the name suggests inflammation is confined to the colon (colitis); therefore, unlike CD surgical removal of the colon can be curative in UC. IBD is associated with increased morbidity, hospitalisations, surgery, medical and nutritional complications and high health care costs. For people with this condition it can be debilitating and result in poor quality of life and life-long ill health.

CD cannot yet be cured, and therefore disease management focuses on pharmacological interventions that control symptoms and maintain remission[17] with many patients requiring surgery at some stage during their disease course[18]. Several nutritional approaches aimed at maintaining remission in CD have been investigated, including fish oils, probiotics and enteral nutrition, although none have translated to effective mainstream management for adult CD[6,19,20]. In recent years, vitamin D has emerged as a candidate of interest as an adjunctive treatment in CD. In this context, most of the published human studies of vitamin D as adjunctive treatment of IBD have been conducted in CD, and consequently CD constitutes much of the focus of this review paper.

Vitamin D deficiency is common in Crohn's disease: cause or effect?

Vitamin D deficiency is common in IBD. Prevalence of deficiency may range from 35 to 100% in CD[21], when deficiency is defined as circulating 25-hydroxyvitamin D (25(OH)D) <50 nmol/l[22] and applied across a range of published studies. Studies reporting suboptimal vitamin D status in CD have considerable methodological variation, including differences in the definitions of deficiency, sample size, geographic region, season, characteristics of the study cohorts and in the vitamin D assay used. General debate around what level of 25(OH)D is considered deficient or insufficient further complicates the issue[23], and whether a higher threshold for deficiency should be applied in disease states such as CD. Despite differences in these studies, it is clear that suboptimal vitamin D status is common in CD. Indeed, this is not surprising considering the high background level of vitamin D deficiency in healthy individuals and the added risk of deficiency conferred by a chronic, inflammatory gastrointestinal disease.

In CD, both generic and disease-specific factors contribute to circulating levels of 25(OH)D attained. These include sunlight exposure, skin pigmentation, indoor sedentary lifestyles, obesity, cigarette smoking, and dietary and supplementary vitamin D intake. For those with CD, there are additional risk factors for deficiency such as malabsorption, intestinal inflammation, intestinal resection, corticosteroid usage and poor dietary intake. High prevalence of suboptimal vitamin D status is not disputed in IBD, but it is not clear whether this has the capacity to influence CD initiation and severity or is merely a consequence of the disease.

Vitamin D status as a risk factor for developing inflammatory bowel disease

The exact cause of IBD remains unknown; however, the disease is thought to result from a complex interaction between immunological, genetic and environmental factors. Vitamin D status is one such postulated environmental risk factor [24–26]. Epidemiological studies show a geographic variation in the incidence of IBD, with a higher incidence in countries of more northern latitudes, mirroring sunlight patterns and likely to reflect vitamin D levels. Studies in the USA[25,27] and Europe have linked latitude to risk of both CD and UC[28–30].

Two separate published analyses, based on data from women who participated in the Nurses' Health studies in the USA, support this association between higher latitude and higher incidence of IBD[25,27]. Khalili *et al*. reported a significant increase in incidence of both CD and UC according to more northerly latitude of residence[25]. The authors further analysed the latitude of residence across a number of time points and found the strongest association at age 30 years. For example, compared with women living at northern latitudes at age 30 years, the multivariate-adjusted hazard ratio for women living in southern latitudes was 0·48 (95% CI 0·30, 0·77) for CD and 0·62 (95% CI 0·42, 0·90) for UC [25]. Since IBD is likely to develop over a considerable period of time, understanding the role of risk factors, such as latitude of residence or vitamin D status, at different age points may be useful. In a further study, using an estimate of predicted vitamin D status, Ananthakrishnan *et al.*[27] showed that higher predicted 25(OH)D was significantly associated with a reduced risk for incident CD (hazard ratio 0·54; P_{trend} 0·02; 95% CI 0·30, 0·99) but not for UC (hazard ratio 0·65; P_{trend} 0·17; 95% CI 0·34, 1·25).

To date, investigations into vitamin D and risk of IBD have not directly measured circulating 25(OH)D levels, but instead have used surrogate markers such as latitude of residence or an index for predicted vitamin D[31] status. Residing at southern latitudes would be expected to increases an individual's access to the UVB rays responsible for cutaneous vitamin D synthesis. In general, it is thought that for people living above 40°N, for

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

Table 1. Overview of reported associations between circulating 25-hydroxyvitamin D (25(OH)D) levels and outcomes of disease activity in patients with Crohn's disease (CD)

Reference	Year	Region	CD *n*	Disease activity score CDAI/HBI	Systemic inflammation CRP	Intestinal inflammation Faecal calprotectin
Raftery *et al.*[43]	2014	Ireland	85	X (CDAI)	X	√, inverse
Garg *et al.*[42]	2013	Australia	40	X (HBI)	X	√ inverse
Jorgensen *et al.*[78]	2013	Denmark	182	√ inverse (CDAI)	X	–
Kelly *et al.*[66]	2011	Ireland	75	X (CDAI)	X	–
Ulitsky *et al.*[79] (total *n*~785)	2011	USA	403	√ inverse (HBI)	–	–
Other disease outcomes						
Ananthakrishnan *et al.*[44]	2013	USA	1769	Low 25(OH)D and higher risk of surgery and hospitalisation		
Zator *et al.*[45]	2013	USA	74	Low 25(OH)D and loss of response to drug therapy		

CRP, C-reactive protein; CDAI, Crohn's disease activity index; HBI, Harvey–Bradshaw index.
Information in parentheses specifies the method of disease activity assessment used. √ indicates a significant association between 25(OH)D levels and the marker in question, the direction of the association is stated as positive or inverse. X indicates no significant association reported between 25(OH)D levels and the marker in question. Dash (–) indicates that the disease marker was not assessed/reported.

example north of Rome or Chicago, sunlight alone is unlikely to maintain adequate vitamin D status all year around, and thus requires a reliance on dietary sources and body stores of vitamin D[32].

Geographic location may, of course, reflect disease risk factors other than 25(OH)D levels, for instance, genetic or environmental influencers. Although newer theories suggest that other components of sunlight (e.g. UVA non-vitamin D-making rays) might also have health effects, independent of vitamin D[33]. The association with disease incidence and latitude is not unique to IBD; there is supporting parallel evidence of a north–south gradient in the incidence of other autoimmune and gastrointestinal diseases, including rheumatoid arthritis[34] and colorectal cancer[35–37]. For colorectal cancer, geographic region[37], predicted[38] and measured pre-diagnostic circulating 25(OH)D have been linked with disease risk[36].

Vitamin D status and associations with disease severity in Crohn's disease

The relationship between circulating 25(OH)D concentrations and disease activity in CD has been explored in several cross-sectional studies, yet the finding remain inconsistent. Some studies suggest that low 25(OH)D is associated with more active disease, whereas others do not support this premise, based on studies collectively comprising approximately 800 CD participants (Table 1). Understanding this association is complicated by the different parameters applied by studies to capture disease activity, which typically include: (a) clinical activity scores, namely the Crohn's disease activity index (CDAI), currently the gold standard[39] or the Harvey–Bradshaw index;[40] (b) C-reactive protein (CRP) as a marker of systemic inflammation; (c) faecal calprotectin[41] as a marker of intestinal inflammation.

For systemic inflammation, as determined by CRP, current studies broadly agree and show a lack of association with 25(OH)D levels. The two studies to date that have investigated intestinal inflammation using faecal calprotectin show a significant inverse association between 25(OH)D and disease activity[42,43]. Analysis according to clinical disease activity scores (CDAI or Harvey–Bradshaw index), however, lack agreement (Table 1) in cross-sectional studies. Importantly, some study populations included only patients in disease remission[21], whereas others comprised patients with active disease and those in remission[42]. In addition to disease activity, other authors have indicated an association between low 25(OH)D and increased need for surgery and hospitalisations for CD[44] which are considered to reflect more severe disease. An association with low vitamin D levels and loss of response to immunomodulatory treatments has also been reported[45].

Collectively, observational studies provide evidence of the co-existence of lower vitamin D levels and more active disease, nevertheless, the issue of 'cause and effect' cannot be answered by these studies. The question remains as to whether interventions to raise 25(OH)D levels by vitamin D supplementation in these patients would modify disease activity or alter disease progression? This question is now beginning to be addressed by intervention studies.

Vitamin D as therapy for Crohn's disease: evidence from intervention studies

Currently there are few published randomised controlled trials (RCTs) that have investigated vitamin D as a therapeutic agent to prevent relapse or induce remission in CD (Table 2). The key RCT study published by Jorgensen *et al.*[14] showed a non-significant reduction in relapse rates in CD patients treated with 30 μg (1200 IU) vitamin D_3 daily for 12 months. Patients (*n* 98) were in clinical remission at enrolment, and at 12 months the relapse rates were 12 and 29% in the vitamin D treated and placebo groups, respectively ($P = 0{\cdot}06$). An open-label study from 2009, designed to examine the effects of vitamin D on bone markers in CD (*n* 37)[46] also captured effects on disease activity. Patients were treated with either active vitamin D or 25 μg (1000 IU) D_3 daily for 12 months; the authors reported a significant short-term reduction

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

Table 2. Intervention studies of vitamin D supplementation to prevent relapse in adults with Crohn's disease (CD)

Reference	Year	CD *n*	Disease activity at enrolment	Study design	Dose of vitamin D	Duration of supplementation in months	Outcome measure	Outcome
Jorgensen *et al.*[14]	2010	98	Inactive	RCT	30 μg (1200 IU) daily D_3	12	Relapse at 1 year defined by CDAI	13% *v.* 29% relapse for D_3 *v.* placebo (NS: $P = 0{\cdot}06$)
Yang *et al.*[47]	2013	18	Active (mild-moderate)	Open label	Titrated dose of D_3 to achieve serum 25(OH)D 100 nmol/l	6	Change in CDAI	Significant reduction in CDAI score
Milhiller *et al.*[46]	2009	37	Inactive	Open label	Active vitamin D and D_3	12	Change in CDAI/ CRP	Significant reduction in CDAI score and CRP

CRP, C-reactive protein; CDAI, Crohn's disease activity index; RCT, randomised controlled trial.

in disease activity (CDAI and CRP) with a more pronounced effect noted for the active form of vitamin D[46].

More recently, Yang *et al.*[47] applied a protocol designed to focus on achieving circulating 25(OH)D levels of 100 nmol/l rather than on administrating a predefined fixed daily dose of vitamin D. In this small study (*n* 18), patients with mild to moderately active CD were supplemented with oral vitamin D_3; this dose was initiated at 25 μg (1000 IU) daily and escalated up to a maximum of 125 μg (5000 IU), to achieve the target circulating 25(OH)D of 100 nmol/l. The key finding was a significant reduction in CDAI scores at 6 months. Focusing on achieving a target 25(OH)D level is interesting, since some authors suggest that levels of 75 nmol/l or higher may be required to observe changes in non-skeletal outcomes[48,49]. Preliminary findings from an RCT from our group[50], showed that CD patients who achieved 25(OH)D levels ≥75 nmol/l have significantly lower serum CRP than those with levels below this threshold; this was in response to a 3-month treatment with 50 μg (2000 IU)/d vitamin D_3 in patients in remission.

Taken together, results from intervention studies suggest that vitamin D supplementation may reduce markers of disease activity in CD. Although at this point, there is insufficient evidence to support vitamin D as an anti-inflammatory therapy. There is a continued need for high-quality RCT for vitamin D therapy in IBD. In essence, vitamin D clinical trials should be well-designed and employ outcome measures compatible with other therapeutic studies. Ideally, evidence of intestinal mucosal healing is a desirable outcome measure in response to vitamin D supplementation; although this requires an invasive endoscopic examination, which is logistically challenging for many nutrition studies. As an alternative, measurement of faecal calprotectin as a surrogate marker of intestinal inflammation may be useful[41]. Furthermore, there is interest in other endpoint measures such patient-reported outcomes that may be applicable to clinical trials[51]. Other aspects to consider include factors predicting response and failure to vitamin D treatments. For example, is response determined by CD characteristics, phenotype or genotype or influenced by vitamin D genotype? In line with this, an RCT in tuberculosis identified a better response to adjunctive vitamin D therapy in participants with the tt genotype of the TaqI vitamin D receptor polymorphism [52].

Vitamin D as therapy: is there a therapeutic zone for 25-hydroxyvitamin D levels?

In intervention studies, the level of circulating 25(OH)D achieved as well as the dose of supplemental vitamin D are likely to be important factors in understanding the therapeutic response. While circulating 25(OH)D >50 nmol/l has been deemed adequate for bone health,[22] immunomodulatory effects may require higher levels. Indeed, concentrations of >75, or indeed 90–100 nmol/l 25(OH)D have been proposed for multiple health outcomes [48], although others argue the case for even higher

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

levels of 100–200 nmol/l [23]. In the context of CD, a target 25(OH)D concentration deemed optimal for anti-inflammatory or therapeutic effects, if any, is not known. In the few RCTs of vitamin D in CD conducted to date (Table 2) levels of 75–100 nmol/l 25(OH)D have been achieved. Jorgensen *et al.*, for instance, achieved a mean 25(OH)D just below 100 nmol/l (mean 96 (SD 27) nmol/l) in response to 30 μg (1200 IU)/d vitamin D treatment; this was accompanied by a non-significant reduction in CD relapse rates at 1 year[14]. Preliminary findings from our pilot intervention study showed that 50 μg (2000 IU)/d vitamin D raised levels from 69 to 92 nmol/l at 3 months, which was accompanied by a modest reduction in CRP but only in participants who achieved serum 25(OH)D >75 nmol/l[50]. Yang *et al.*[47] specifically designed their study to achieve a target circulating 25(OH)D of 100 nmol/l, and achieving this target level was associated with short-term improvements in disease activity.

Vitamin D therapy poses additional challenges compared with other therapeutic trials. In pharmaceutical trials, the placebo group is typically unexposed to the therapeutic intervention, whereas in vitamin D clinical trials the placebo group have an existing background level of vitamin D, which may vary in participants. Both Jorgensen *et al.*[14] and Raftery *et al.*[50] reported a good baseline 25(OH)D level at study enrolment (69 nmol/l for both studies). It is plausible that supplementation in a vitamin-D-deficient CD group would be of greater benefit compared with a replete group. It is, as yet, unclear how baseline vitamin D status, levels attained post-treatment and the magnitude of change from baseline influence treatment response.

Thus far, modest changes in disease activity in CD have been observed in intervention studies that achieved vitamin D levels in the region of 75–100 nmol/l. On balance, there is as yet insufficient evidence to make a judgement about a therapeutic or immunomodulatory zone for 25(OH)D specifically for CD. Clinically, our group currently apply a cut-off of 25(OH)D <50 nmol/l for vitamin D deficiency. According to the Institute of Medicine report,[22] levels higher than 50 nmol/l are considered to cover the requirements of at least 97·5% of the healthy population. The Endocrine Society guidelines[23], however, define vitamin D deficiency as 25(OH)D <50 nmol/l, but consider <75 nmol/l as vitamin D insufficiency[23]. Although there remains debate about disease-specific and health outcome-specific levels, in the meantime, it seems prudent that, at a minimum, clinical management should aim to prevent vitamin D deficiency in CD.

Vitamin D as therapy in Crohn's disease: evidence of underlying mechanisms

During the 1980s vitamin D receptors were identified on cells of the immune system[53,54] sparking interest in immunemodulating effects of vitamin D. For IBD, there is a compelling body of evidence from animal models that vitamin D has the capacity to alter immune responses[11,55–57]. Vitamin D deficiency, for example, accelerates the development of experimental colitis in IL-10 knock-out mice,[12] whereas treatment with dietary vitamin D and calcium appear to protect against the development of inflammation[58]. Down-regulation of inflammatory cytokines, notable, TNF-α and interferon γ and up-regulation of IL-10 has been demonstrated[58,59] in response to vitamin D. Newer directions focus on effects of vitamin D as a late regulator of immune responses[56] effects on autophagy[60], on gut barrier integrity[61,62] and on the gut microbiome[63]. Recently, Cantorna and Waddell[56] proposed vitamin D as a late regulator of T-cell function, which acts to turn off chronically activated T-cells through the vitamin D receptor; in contrast resting T-cells remain unresponsive to vitamin D because they do not express vitamin D receptors until late after activation[56]. Relevant to IBD, there is evidence that vitamin D deficiency may compromise the gastrointestinal mucosal barrier, whereas active vitamin D appears to promotes epithelial integrity through up-regulation of tight junction proteins zonula occcludens-1 and claudin-1[61,62]. Some reports suggest changes in the gut microbial composition in animal models[63] in response to vitamin D. Despite immense interest in the gut microbiome[64,65] this has yet to be investigated in response to vitamin D therapy in CD.

Although some parallels exist, the degree to which the immune effects observed in animal models translate to human IBD is not fully understood. Consistent with experimental findings, Bartels *et al.*[15] showed that the active form of vitamin D (1,25-dihydroxyvitamin D_3) increased IL-10 production and reduced interferon γ in T-cells derived from patients with CD. Similarly, we showed an inverse association between vitamin D deficiency and circulating IL-10[66] in a cross-sectional study of CD; however, no association was note for TNF-α. Arguable, this suggests that patients who are vitamin D deficient have lower IL-10 production and reduced anti-inflammatory capacity. In contrast, findings from other authors do not support this reduction in IL-10 in response to high-dose vitamin D supplementation in CD[47].

There is emerging, albeit inconsistent, mechanistic data from vitamin D intervention studies in CD. Increased IL-6 was reported, based on experiments on activated T-cells derived from patients (*n* 10) treated with 30 μg (1200 IU) in an RCT [67]. This finding appears at odds with putative anti-inflammatory effects and may reflect a paradoxical role for IL-6 in this clinical setting. Notably, in an open label study by Yang *et al.*[47], a series of inflammatory cytokines (TNF-α, IL-17 and IL-10) remained unchanged in response to vitamin D supplementation, even though circulating levels of 25(OH)D of 100 nmol/l were achieved. Others hypothesise that therapeutic response of vitamin D may be mediated in part by effects on the intestinal barrier[68,69]. Preliminary results [50] from our group suggest that vitamin D supplementation (50 μg (2000 IU)/d) may maintain intestinal permeability and barrier integrity in CD, but the findings from this pilot study require further investigation. Clearly, more mechanistic studies are needed to identify and confirm the mechanism by which vitamin may exert anti-inflammation effects in CD.

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

Vitamin D and multiple health outcomes in inflammatory bowel disease

Vitamin D may modify other health outcomes in IBD beyond bone and immune responses; this includes impacts on colorectal cancer risk and muscle strength. People with IBD are at increased risk of developing colorectal cancer due to chronic inflammation. In large population studies growing, although not entirely consistent, evidence suggests vitamin D as a plausible candidate for colorectal cancer prevention[36–38,70]. Ananthakrishnan *et al.*[71], recently reported an increased risk of colorectal cancer in a cohort (*n* 2809) of patients with IBD who were vitamin D deficient (25(0H)D <50 nmol/l). Furthermore, a gradient-response was noted; each increment increase (2·5 nmol/l) in 25(OH)D concentration was associated with an 8% reduction in risk of colorectal cancer (OR 0·92; 95% CI 0·88, 0·96) [71]. Although this suggests that vitamin D may have a chemoprevention role in IBD, the finding needs to be replicated in further cohorts. Of note, this study enrolled patients who had an existing 25(OH)D measurement which may bias the study cohort; for example, patients in whom vitamin D assessment was clinically indicated may also have disease characteristics which confer an increased risk of cancer, independent of vitamin D status.

Reduced muscle strength has been documented in CD[72] and while multifactorial in origin, one current theory implicates vitamin D status. An important focus of poor muscle function in CD is its role in exacerbating chronic fatigue, a common and often debilitating symptom reported by patients[73]. There is some evidence that vitamin D supplementation improves muscle strength[74,75] at least in older adults. Equally, increasing circulating 25(OH)D >75 nmol/l may result in reduced fatigue severity, although by undefined mechanisms[76]. In CD, preliminary findings from an RCT showed a significant reduction in self-reported fatigue in patients who achieved a 25(OH)D level >75 nmol/l in response to 50 µg (2000 IU) oral supplemental vitamin D[77]. Overall the findings remain inconclusive and further evidence would be required to understand if vitamin D plays a role in preserving muscle function, in cancer prevention and in other health outcomes in IBD.

Conclusion: research agenda and future directions

Several strands of evidence suggest vitamin D as a potential anti-inflammatory therapy for conditions such as IBD. Ultimately this potential will be judged based on a proven efficacy to induce or prolong disease remission as an adjunct to medical therapy. To date, intervention studies of vitamin D treatment for IBD are few, primarily conducted in CD and as yet provide insufficient evidence for translation to clinical practice.

For future studies, it may be important to consider how vitamin D-specific and IBD-specific factors influence response to vitamin D treatment. For example, baseline vitamin D status, supplemental doses of vitamin D, subsequent circulating level of 25(OH)D achieved and magnitude of change from baseline. Moreover, other factors such as disease phenotype and genotype and effects of IBD medications may impact on response. A clearer understanding of these and other factors such as the putative 'therapeutic zone' for vitamin D levels may help inform clinical consensus. If proven effective, vitamin D could offer a safe, inexpensive therapeutic strategy for IBD that provides additional bone benefits.

In the interim, at a minimum we should aim to prevent vitamin D deficiency in IBD. It seems reasonable to consider and investigate if there is an IBD-specific optimal 25(OH)D level. So what of the role of vitamin D as a novel anti-inflammatory therapy in IBD? This topic continues to attract interest; there is indeed some unavoidable hype, some hope or promise from emerging scientific data, but a dearth of evidence. There is an ongoing need for high-quality well-designed clinical trials and mechanistic studies to determine whether the emerging anti-inflammatory effects for vitamin D translate into tangible clinical benefits for patients with chronic debilitating diseases such as IBD.

Acknowledgements

I would like to sincerely thank the Nutrition Society for the award of the Sir David Cuthbertson Medal and for the invitation to present a lecture, on which this paper is based.

Financial Support

None.

Conflicts of Interest

None.

Authorship

M. O'S. wrote the manuscript based on a lecture presented at the Nutrition Society meeting.

References

1. Theodoratou E, Tzoulaki I, Zgaga L *et al.* (2014) Vitamin D and multiple health outcomes: umbrella review of systematic reviews and meta-analyses of observational studies and randomised trials. *BMJ* **348**, g2035.
2. Cantorna MT (2008) Vitamin D and multiple sclerosis: an update. *Nutr Rev* **66**, S135–S138.
3. Cantorna MT (2012) Vitamin D, multiple sclerosis and inflammatory bowel disease. *Arch Biochem Biophys* **523**, 103–106.
4. Holick MF (2005) The vitamin D epidemic and its health consequences. *J Nutr* **135**, 2739S–2748S.

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

5. Shapira Y, Agmon-Levin N & Shoenfeld Y (2010) Geoepidemiology of autoimmune rheumatic diseases. *Nat Rev Rheumatol* **6**, 468–476.
6. O'Sullivan M (2009) Nutrition in Crohn's disease. *Proc Nutr Soc* **68**, 127–134.
7. Vazquez MA, Lopez E, Montoya MJ *et al.* (2012) Vertebral fractures in patients with inflammatory bowel disease compared with a healthy population: a prospective case-control study. *BMC Gastroenterol* **12**, 47.
8. Bernstein C & Leslie W (2004) Osteoporosis and inflammatory bowel disease. *Aliment Pharmacol Therap* **19**, 941–952.
9. Bernstein CN, Blanchard JF, Leslie W *et al.* (2000) The incidence of fracture among patients with inflammatory bowel disease. A population-based cohort study. *Ann Intern Med* **133**, 795–799.
10. British-Society-of-Gastroenterology (2007) Guidelines for osteoporosis in inflammatory bowel disease and coeliac disease. http://wwwbsgorguk/clinical-guidelines/ibd/guidelines-for-osteoporosis-in-inflammatory-bowel-disease-and-coeliac-diseasehtml (accessed February 2014).
11. Cantorna MT (2010) Mechanisms underlying the effect of vitamin D on the immune system. *Proc Nutr Soc* **69**, 286–289.
12. Cantorna MT, Munsick C, Bemiss C *et al.* (2000) 1,25-Dihydroxycholecalciferol prevents and ameliorates symptoms of experimental murine inflammatory bowel disease. *J Nutr* **130**, 2648–2652.
13. Ananthakrishnan AN (2014) Environmental risk factors for inflammatory bowel diseases: a review. *Dig Dis Sci* (Epublication ahead of print version).
14. Jorgensen SP, Agnholt J, Glerup H *et al.* (2010) Clinical trial: vitamin D3 treatment in Crohn's disease – a randomized double-blind placebo-controlled study. *Aliment Pharmacol Ther* **32**, 377–383.
15. Bartels LE, Jorgensen SP, Agnholt J *et al.* (2007) 1,25-dihydroxyvitamin D3 and dexamethasone increase interleukin-10 production in CD^{4+} T cells from patients with Crohn's disease. *Int Immunopharmacol* **7**, 1755–1764.
16. Crohn B, Ginzburg L & Oppenheimer G (1932) Regional ileitis, a pathologic and clinical entity. *JAMA* **99**, 1323–1329.
17. Mowat C, Cole A, Windsor A *et al.* (2011) Guidelines for the management of inflammatory bowel disease in adults. *Gut* **60**, 571–607.
18. Vester-Andersen MK, Prosberg MV, Jess T *et al.* (2014) Disease course and surgery rates in inflammatory bowel disease: a population-based, 7-year follow-up study in the era of immunomodulating therapy. *Am J Gastroenterol* **109**, 705–714.
19. Jonkers D, Penders J, Masclee A *et al.* (2012) Probiotics in the management of inflammatory bowel disease: a systematic review of intervention studies in adult patients. *Drugs* **72**, 803–823.
20. Hedin C, Whelan K & Lindsay JO (2007) Evidence for the use of probiotics and prebiotics in inflammatory bowel disease: a review of clinical trials. *Proc Nutr Soc* **66**, 307–315.
21. Suibhne TN, Cox G, Healy M *et al.* (2012) Vitamin D deficiency in Crohn's disease: prevalence, risk factors and supplement use in an outpatient setting. *J Crohns Colitis* **6**, 182–188.
22. Institute-of-Medicine (2011) Dietary Reference Intakes for Calcium and Vitamin D. Washington DC, USA: The National Academies Press.
23. Holick MF, Binkley NC, Bischoff-Ferrari HA *et al.* (2011) Evaluation, treatment, and prevention of vitamin D deficiency: an Endocrine Society clinical practice guideline. *J Clin EndocrinolMetab* **96**, 1911–1930.
24. Danese S & Fiocchi C (2006) Etiopathogenesis of inflammatory bowel diseases. *World J Gastroenterol* **12**, 4807–4812.
25. Khalili H, Huang ES, Ananthakrishnan AN *et al.* (2012) Geographical variation and incidence of inflammatory bowel disease among US women. *Gut* **61**, 1686–1692.
26. Mouli VP & Ananthakrishnan AN (2014) Review article: vitamin D and inflammatory bowel diseases. *Aliment Pharmacol Ther* **39**, 125–136.
27. Ananthakrishnan AN, Khalili H, Higuchi LM *et al.* (2012) Higher predicted vitamin D status is associated with reduced risk of Crohn's disease. *Gastroenterology* **142**, 482–489.
28. Armitage EL, Aldhous MC, Anderson N *et al.* (2004) Incidence of juvenile-onset Crohn's disease in Scotland: association with northern latitude and affluence. *Gastroenterology* **127**, 1051–1057.
29. Nerich V, Jantchou P, Boutron-Ruault MC *et al.* (2011) Low exposure to sunlight is a risk factor for Crohn's disease. *Aliment Pharmacol Ther* **33**, 940–945.
30. Shivananda S, Lennard-Jones J, Logan R *et al.* (1996) Incidence of inflammatory bowel disease across Europe: is there a difference between north and south? Results of the European Collaborative Study on inflammatory bowel disease (EC-IBD). *Gut* **39**, 690–697.
31. Bertrand KA, Giovannucci E, Liu Y *et al.* (2012) Determinants of plasma 25-hydroxyvitamin D and development of prediction models in three US cohorts. *Br J Nutr* **108**, 1889–1896.
32. Kiely M & Black LJ (2012) Dietary strategies to maintain adequacy of circulating 25-hydroxyvitamin D concentrations. *Scand J Clin Lab Investig Suppl* **243**, 14–23.
33. Liu D, Fernandez BO, Hamilton A *et al.* (2014) UVA irradiation of human skin vasodilates arterial vasculature and lowers blood pressure independently of nitric oxide synthase. *J Investig Dermatol* **134**, 1839–1846.
34. Vieira V, Hart J, Webster T *et al.* (2010) Association between residences in U.S. northern latitudes and rheumatoid arthritis: a spatial analysis of the Nurses' Health Study. *Environ Health Perspect* **118**, 957–961.
35. Gorham ED, Garland CF, Garland FC *et al.* (2007) Optimal vitamin D status for colorectal cancer prevention: a quantitative meta analysis. *Am J Prev Med* **32**, 210–216.
36. Jenab M, Bueno-de-Mesquita HB, Ferrari P *et al.* (2010) Association between pre-diagnostic circulating vitamin D concentration and risk of colorectal cancer in European populations: a nested case-control study. *BMJ* **340**, b5500.
37. Giovannucci E (2013) Epidemiology of vitamin D and colorectal cancer. *Anti-cancer Agents Med Chem* **13**, 11–19.
38. Jung S, Qian ZR, Yamauchi M *et al.* (2014) Predicted 25 (OH)D score and colorectal cancer risk according to vitamin D receptor expression. *Cancer Epidemiol Biomark Prevent* **23**, 1628–1637.
39. Best WR, Becktel JM, Singleton JW *et al.* (1976) Development of a Crohn's disease activity index. National Cooperative Crohn's Disease Study. *Gastroenterology* **70**, 439–444.
40. Best WR (2006) Predicting the Crohn's disease activity index from the Harvey-Bradshaw Index. *Inflamm Bowel Dis* **12**, 304–310.
41. Benitez JM, Meuwis MA, Reenaers C *et al.* (2013) Role of endoscopy, cross-sectional imaging and biomarkers in Crohn's disease monitoring. *Gut* **62**, 1806–1816.
42. Garg M, Rosella O, Lubel JS *et al.* (2013) Association of circulating vitamin D concentrations with intestinal but not systemic inflammation in inflammatory bowel disease. *Inflamm Bowel Dis* **19**, 2634–2643.
43. Raftery T, Smith S, O'Morain C *et al.* (2014) Serum vitamin D concentrations are associated with markers of

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press

intestinal but not systemic inflammation in Crohn's disease in remission. *Nutrients* **6**, S2759–2919.
44. Ananthakrishnan AN, Cagan A, Gainer VS *et al.* (2013) Normalization of plasma 25-hydroxy vitamin D is associated with reduced risk of surgery in Crohn's disease. *Inflamm Bowel Dis* **19**, 1921–1927.
45. Zator ZA, Cantu SM, Konijeti GG *et al.* (2014) Pretreatment 25-hydroxyvitamin D levels and durability of anti-tumor necrosis factor-alpha therapy in inflammatory bowel diseases. *JPEN J Parenteral Enteral Nutr* **38**, 385–391.
46. Miheller P, Muzes G, Hritz I *et al.* (2009) Comparison of the effects of 1,25 dihydroxyvitamin D and 25 hydroxyvitamin D on bone pathology and disease activity in Crohn's disease patients. *Inflamm Bowel Dis* **15**, 1656–1662.
47. Yang L, Weaver V, Smith JP *et al.* (2013) Therapeutic effect of vitamin d supplementation in a pilot study of Crohn's patients. *Clin Transl Gastroenterol* **4**, e33.
48. Bischoff-Ferrari HA (2008) Optimal serum 25-hydroxyvitamin D levels for multiple health outcomes. *Adv Exp Med Biol* **624**, 55–71.
49. Bischoff-Ferrari HA, Giovannucci E, Willett WC *et al.* (2006) Estimation of optimal serum concentrations of 25-hydroxyvitamin D for multiple health outcomes. *Am J Clin Nutr* **84**, 18–28.
50. Raftery T, Martineaux AM, Greiller C *et al.* (2013) Effects of vitamin D supplementation on intestinal permeability, plasma cathelicidin and human beta-defensin-2 in Crohn's disease: results from a randomised double-blind placebo-controlled study. *Gastroenterology* **144**, S226–S227.
51. Levesque BG, Sandborn WJ, Ruel J *et al.* (2014) Converging goals of treatment for inflammatory bowel disease, from clinical trials and practice. *Gastroenterology* (Epublication ahead of print version).
52. Martineau AR, Timms PM, Bothamley GH *et al.* (2011) High-dose vitamin D(3) during intensive-phase antimicrobial treatment of pulmonary tuberculosis: a double-blind randomised controlled trial. *Lancet* **377**, 242–250.
53. Provvedini DM, Tsoukas CD, Deftos LJ *et al.* (1983) 1,25-dihydroxyvitamin D_3 receptors in human leukocytes. *Science* **221**, 1181–1183.
54. Bhalla AK, Amento EP, Clemens TL *et al.* (1983) Specific high-affinity receptors for 1,25-dihydroxyvitamin D_3 in human peripheral blood mononuclear cells: presence in monocytes and induction in T lymphocytes following activation. *J Clin Endocrinol Metab* **57**, 1308–1310.
55. Cantorna MT (2006) Vitamin D and its role in immunology: multiple sclerosis, and inflammatory bowel disease. *Prog Biophys Mol Biol* **92**, 60–64.
56. Cantorna MT & Waddell A (2014) The vitamin D receptor turns off chronically activated T cells. *Ann N Y Acad Sci* **1317**, 70–75.
57. Cantorna MT, Zhu Y, Froicu M *et al.* (2004) Vitamin D status, 1,25-dihydroxyvitamin D_3, and the immune system. *Am J Clin Nutr* **80**, 1717S–1720S.
58. Zhu Y, Mahon B, Froicu M *et al.* (2005) Calcium and 1,25-dihydroxyvitamin D3 target the TNF-a pathway to suppress experimental inflammatory bowel disease. *Eur J Immunol* **35**, 217–224.
59. Froicu M, Zhu Y & Cantorna MT (2006) Vitamin D receptor is required to control gastrointestinal immunity in IL-10 knockout mice. *Immunology* **117**, 310–318.
60. Wu S, Zhang YG, Lu R *et al.* (2014) Intestinal epithelial vitamin D receptor deletion leads to defective autophagy in colitis. *Gut* (Epublication ahead of print version).
61. Kong J, Zhang Z, Musch MW *et al.* (2008) Novel role of the vitamin D receptor in maintaining the integrity of the intestinal mucosal barrier. *Am J Physiol Gastrointest Liver Physiol* **294**, G208–G216.
62. Zhao H, Zhang H, Wu H *et al.* (2012) Protective role of 1,25(OH)2 vitamin D3 in the mucosal injury and epithelial barrier disruption in DSS-induced acute colitis in mice. *BMC Gastroenterol* **12**, 57.
63. Ooi JH, Li Y, Rogers CJ *et al.* (2013) Vitamin D regulates the gut microbiome and protects mice from dextran sodium sulfate-induced colitis. *J Nutr* **143**, 1679–1686.
64. Hart AL & Hendy P (2014) The microbiome in inflammatory bowel disease and its modulation as a therapeutic manoeuvre. *Proc Nutr Soc* **73**, 452–456.
65. O'Connor EM, O'Herlihy EA & O'Toole PW (2014) Gut microbiota in older subjects: variation, health consequences and dietary intervention prospects. *Proc Nutr Soc* **73**, 441–451.
66. Kelly P, Suibhne TN, O'Morain C *et al.* (2011) Vitamin D status and cytokine levels in patients with Crohn's disease. *Int J Vitam Nutr Res* **81**, 205–210.
67. Bendix-Struve M, Bartels LE, Agnholt J *et al.* (2010) Vitamin D3 treatment of Crohn's disease patients increases stimulated T cell IL-6 production and proliferation. *Aliment Pharmacol Ther* **32**, 1364–1372.
68. Raftery T, O'Morain CA & O'Sullivan M (2012) Vitamin D: new roles and therapeutic potential in inflammatory bowel disease. *Curr Drug Metab* **13**, 1294–1302.
69. Garg M, Lubel JS, Sparrow MP *et al.* (2012) Review article: vitamin D and inflammatory bowel disease – established concepts and future directions. *Aliment Pharmacol Ther* **36**, 324–344.
70. Giovannucci E (2010) Epidemiology of vitamin D and colorectal cancer: casual or causal link? *J Steroid Biochem Mol Biol* **121**, 349–354.
71. Ananthakrishnan AN, Cheng SC, Cai T *et al.* (2014) Association between reduced plasma 25-hydroxy vitamin D and increased risk of cancer in patients with inflammatory bowel diseases. *Clin Gastroenterol Hepatol* **12**, 821–827.
72. van Langenberg DR, Della Gatta P, Warmington SA *et al.* (2014) Objectively measured muscle fatigue in Crohn's disease: correlation with self-reported fatigue and associated factors for clinical application. *J Crohns Colitis* **8**, 137–146.
73. Jelsness-Jorgensen LP, Bernklev T, Henriksen M *et al.* (2011) Chronic fatigue is more prevalent in patients with inflammatory bowel disease than in healthy controls. *Inflamm Bowel Dis* **17**, 1564–1572.
74. Beaudart C, Buckinx F, Rabenda V *et al.* (2014) The effects of vitamin D on skeletal muscle strength, muscle mass and muscle power: a systematic review and meta-analysis of randomized controlled trials. *J Clin Endocrinol* **99**, 4336–4345.
75. Dawson-Hughes B (2012) Serum 25-hydroxyvitamin D and muscle atrophy in the elderly. *Proc Nutr Soc* **71**, 46–49.
76. Roy S, Sherman A, Monari-Sparks MJ *et al.* (2014) Correction of low vitamin D improves fatigue: Effect of correction of low vitamin D in Fatigue Study (EViDiF Study). *N Am J Med Sci* **6**, 396–402.
77. Raftery TC, Lee CS, Cox G *et al.* (2013) Supplemental vitamin D in quiescent Crohn's disease – effects on quality of life, fatigue and muscle strength: results from a double blind placebo controlled study. *Proc Nutr Soc* **72**, E177.
78. Jorgensen SP, Hvas CL, Agnholt J *et al.* (2013) Active Crohn's disease is associated with low vitamin D levels. *J Crohns Colitis* **7**, e407–e413.
79. Ulitsky A, Ananthakrishnan AN, Naik A *et al.* (2011) Vitamin D deficiency in patients with inflammatory bowel disease: association with disease activity and quality of life. *JPEN J Parent Enteral Nutr* **35**, 308–316.

https://doi.org/10.1017/S0029665114001621 Published online by Cambridge University Press