Review

Contribution of Dietary PUFAs and Micronutrients in the protection against Food Allergy Development

Tamara Hoppenbrouwers 1, Jelena H. Cvejić Hogervorst 2, Johan Garssen 3,4, Linette E.M. Willemsen 4 and Harry J. Wichers 5*

1 Wageningen University Food Quality and Design; tamara.hoppenbrouwers@wur.nl
2 University of Novi Sad, Faculty of Medicine, Department of Pharmacy; jelena.cvejic@mf.uns.ac.rs
3 Nutricia Research BV, department immunology, Utrecht; j.garssen@uu.nl
4 Division of Pharmacology, Utrecht Institute for Pharmaceutical Sciences, Utrecht University; L.E.M.Willemsen@uu.nl
5 Wageningen University Food & Biobased Research; harry.wichers@wur.nl

* Correspondence: harry.wichers@wur.nl; Tel.: +31317480175

Abstract: Specific nutrients including n-3 long chain polyunsaturated fatty acids (LCPUFAs), flavonoids, vitamin A, D and E are considered to possess protective properties on human health by impacting on immunological reactions. An ‘inflammation-suppressive’ effect appears to be the common denominator of the beneficial effects of most of these dietary components which may protect against the development of chronic immune disorders such as allergy. However, the majority of these promising data are from preclinical studies such as animal disease models, as the majority of clinical studies only indicate associations. PUFAs, especially n-3 LCPUFAs, have been shown to interact with both the sensitization as well as the effector phase in food allergy. However, it should be noted and realised that PUFAs are highly susceptible to lipid oxidation. Flavonoids and fat-soluble vitamins both contain anti-inflammatory properties and are able to act as anti-oxidants as well. Here, we explore the anti-allergic properties of PUFAs, flavonoids and fat-soluble vitamins in order to create an overview and, more importantly, suggest a strategy to target food allergies using these components and combinations thereof. Dietary n-3 LCPUFAs and the above mentioned micronutrients are promising anti-allergy agents capable of influencing the allergic immune response through multiple and different biological pathways.

Keywords: food allergy; PUFA; flavonoid; vitamin A; vitamin D; vitamin E; immune response; anti-inflammatory.

1. Introduction

Allergic reactions, particularly as a result of food allergy, can be life-threatening. The frequency of reported allergies and the severity of allergies in the Western world increases significantly, and is forecasted to affect e.g. 50% of the EU’s population by 2025 [1]. Food allergy is one of the most common forms of allergy, with a worldwide increasing prevalence of 5-10% highly dependent on the country [2, 3]. The majority of these allergies are triggered by milk, eggs, nuts, wheat, soy and (shell)fish, of which reactions to milk, eggs and peanuts are the most prevalent in children, while peanuts and (shell)fish are the major triggers of allergic reactions in teenagers and adults [4].

The majority of food allergy is known as a type I allergy, indicating that it is mediated by a relative acute response in which immunoglobulin E (IgE) is the pivotal antibody involved. However, also in
absence of allergen specific IgE acute allergic responses may occur upon ingestion of the culprit food. Food contains antigens, which, in case of allergy, are referred to as allergens. Food allergy can be divided into two phases: the sensitization and the effector response.

Allergic sensitization

Allergenic proteins in foods, are recognized by antigen-presenting cells (APCs), of which dendritic cells (DCs) are known to be involved as one of the major cell types aimed at the presentation of antigens to naïve T-cells which may either result in tolerance (normal) or Th2 polarized immunity (allergy) and mixed Th2 and Th1 driven allergen specific immune responses in the chronic phase. DCs reside especially in mucosal tissues of a.o. the nose, lungs, and, for food allergy most important, the oral cavity, intestine and even skin (where DC are referred to as Langerhans cells).

After encountering an allergen, the major histocompatibility complex (MHC) class II positive DCs migrate to the draining lymph nodes, where they present the antigen to naïve CD4+ T-cells. Beyond the DC also other antigen presenting cells such as certain macrophages can be involved in the activation of T-cells. In order to activate these T-cells, two signals are needed: the binding of the T-cell receptor (TCR) specifically recognizing the allergenic epitopes presented in connection with the MHCI of the APC, and interaction of the costimulatory molecules CD28, CTLA-1/4 and LFA-1 on the T-cell with B-7 (CD80/CD86) and ICAM-1 on the dendritic cell [5]. Activated CD4+ T-cells, or T-helper (Th) cells, can roughly be divided into four important groups: Th1, Th2, Th17 and Treg.

Differentiation into either of these subgroups is regulated by many different factors, of which OX40L expression by DC has been reported to be important in driving Th2 differentiation [6]. While Th1 cells are mainly involved in secreting and activating pro-inflammatory cytokines, Th2 cells play a key role in development of type 1 allergy by driving IgE secretion by plasma cells. Treg cells are able to downregulate the proliferation and activation of both Th1 and Th2 cells. Furthermore, Th1 cell derived mediators (IFN-γ) also downregulate Th2 proliferation. As Th2 cells are activated by IL-4 but also secrete IL-4, this acts as a positive feedback loop. By interacting with B-cells and via the release of IL-4, Th2 cells can activate IgE isotype switching and allergen specific antibody production, resulting in allergic sensitization [7, 8]. Beyond binding to allergic effector cells such as mast cells and basophils, IgE can also bind to DCs, further stimulating the immune response.

Allergic effector response

Upon a second encounter with the allergen, IgE that opsonizes e.g. mast cells and basophils binds the allergen, and FceR1 receptor crosslinking results in mast cell activation and degranulation and the induction of the allergic effector response. Mast cells release many different components such as histamine, proteases, heparin, leukotrienes, prostaglandins, cytokines and chemokines, which are all involved in the generation of the allergic symptoms by causing redness, swelling and vasodilation. Sometimes this may even lead to an anaphylactic highly acute reaction within minutes.

The development of the gastro-intestinal and systemic immune system is in part driven by the intestinal microbiome. Defective oral tolerance induction may be a consequence of reduced biodiversity of the microbiota composition and inadequate immune maturation. Microbiome disturbances have been reported to be associated with different types of allergies. Changes in (children’s) microbiome are claimed to be important in the increase in food allergy cases although it is not completely evident what is cause or consequence [9]. Such microbiome changes can be caused by, among others, an increased intake of fat and processed food, reduced intake of dietary fibres, and fruit and vegetables, overconsumption of junk food and the use of antibiotics during pregnancy and/or in early life. A, probably non-exhaustive, sum-up of factors contributing to increased allergy prevalence are thought to be Caesarean section, exposure to pollution (fine dust) and e.g. smoking behaviour [9]. Therefore, the need for prevention and resolving allergy is becoming of major concern. It has been recognized that nutrition plays an important role in the development, maintenance, and appropriate functioning of the immune system, and consequently in the prevention and management of for example food allergies. Food constituents, such as long-chain
polyunsaturated fatty acids (LCPUFAs), flavonoids and micronutrients, may be capable of
influencing the allergic sensitization and/or effector response through multiple biological pathways.
In this review we will focus on the potency of LCPUFAs, flavonoids and fat soluble vitamins (A, D, 
E) in the prevention of food allergy.

2. Long-chain Polyunsaturated Fatty Acids

Polyunsaturated Fatty Acids (PUFAs) are a group of acids that contain more than one double bond
in their molecular structure. The most important PUFA groups are omega-3 (n-3) and omega-6 (n-
6), which are divided by the placement of the first double bond, which is either between the third
and the fourth or the sixth and the seventh carbon of the methyl end (Figure 1). In the n-3 group, α-
linolenic acid (ALA, 18:3n-3) is converted, mostly in the liver, into stearidonic acid (SDA), after
which the chains are elongated by enzymes into long-chain eicosapentanoic acid (EPA, 20:5n-3),
which is converted into docosapentaenoic acid (DPA, 22:5n-3) and then docosahexanoic acid (DHA,
22:6n-3). In the n-6 group, linoleic acid (LA, 18:2n-6) is converted into long-chain arachidonic acid
(AA, 20:4n-6) (Figure 1). These essential n-3 (LC)PUFA fatty acids can be obtained from fatty fish,
such as salmon, tuna, mackerel, herring and sardines and fish oil, and more sustainable sources
such as vegetable oil, nuts and seeds, which are rich in n-3 PUFA ALA and algae oil is rich in n-3
LCPUFAs.

![Figure 1: Schematic overview of the chemical structures of the n-3 and n-6 PUFAs discussed here.](image)

As the result of dietary changes over the last decades, the balance between n-3 and n-6 fatty acids
was disturbed in favour of n-6. N-6 polyunsaturated fatty acid, present in vegetable oils is
increasingly consumed, while the intake of n-3 LCPUFA is, in westernized countries, generally low.
Since n-6 fatty acids are associated with pro-inflammatory and n-3 with anti-inflammatory
activities, the mentioned imbalance is most likely contributing to the rise of non-communicable
diseases, allergies included. Usually recommended consumption of two portions of fatty fish per
week corresponds to 200 mg DHA per day [10]. Due to efficient digestion and absorption,
approximately more than 95% of ingested fatty acids become biologically available [11].

3. Flavonoids

Flavonoids are one of the most abundant classes of polyphenols in food. These components have
the common structure of diphenylpropanes (C6-C3-C6), which is built up of two aromatic rings
linked via three carbons, usually forming an oxygenated heterocycle. Common flavonoids are
divided into subclasses such as flavonols, flavones, flavanones, flavan-3-ols (oligomeric and polymeric forms), proanthocyanidins, anthocyanins, and isoflavones (Figure 2).

**Figure 2**: Schematic overview of some important flavonoids known in relation to food allergy per subclass, discussed in this paper.

Out of more than 4000 flavonoids, 900 are present in the human diet. Dietary flavonoids are contained in commonly consumed plant-derived foods, for example fruits, vegetables, herbs, seeds, grains, and certain beverages such as coffee, tea, and wine. Besides these, other popular sources of flavonoids are dietary supplements including green tea (catechins), grape seed (proanthocyanidins), red apple peel and onion (quercetin), soybeans (isoflavones such as genistein), and many others [12]. In food, flavonoids are usually attached to sugars, acids or alcohols [13].

Due to the high variability of flavonoid components and limited clinical trials data, it is still not possible to define recommended and validated daily doses. Recommended consumption of five servings of fruits and vegetables per day corresponds to a flavonoid intake of approximately 150–300 mg/day [14]. Depending on dietary intake this value could vary due to insufficient consumption of fruit and vegetables as in some developed Western countries and India and China or to specific dietary habits such as high daily intake of coffee or tea [14-16].

The high variety in absorption and bioavailability of flavonoids, consequently influencing biological effects, depends primarily on their structural complexity. However, other factors such as amount of flavonoids consumed, food matrix, glycosylation pattern, gut microbiota, and their interactions with receptors and enzymes are considerably contributing to final health properties and possible protective effects of these components [17-19]. The absorption and metabolism of flavonoids in human body has not been elucidated so far. The ability of flavonoids to cross biological membranes is influenced by factors such as size, hydrophobicity, possible glycosylation, and intracellular reactions [20-22]. It has been shown that some components present in food matrix, such as dietary fibres, divalent metals, and viscous and protein-rich meals are likely to cause detrimental effects on flavonoid bioavailability, which could also be modulated by food composition and culinary techniques [17, 19]. Furthermore, it is most likely that changes in the gut microbiota composition contribute to the large inter-individual variations in bioavailability of flavonoids. The general low level of the specific ingested components in plasma is probably due to the formation of metabolites formed by the gut microbiome or the body’s tissues [17, 22, 23]. However, flavonoids have been measured in human milk samples, indicating indeed uptake of these components from the diet and even transfer into breast milk [24, 25].

Recent evidence has pointed out the anti-inflammatory ability of flavonoids. Flavonoids may be able to influence multiple biological pathways and immune cell functions in the allergic effector response. Flavonoids are also capable of modulating the mechanisms involved in low-grade inflammation and may as well affect the process of allergic sensitization. Furthermore, the
prominent anti-oxidant ability of these components limits the activity of free radicals included in allergic responses [19, 23, 26, 27].

4. Fat-soluble vitamins

Vitamins and their metabolites have an important control function in the immune homeostasis by influencing both, innate and adaptive immune responses. In this section we will focus on fat-soluble vitamins A, D and E, as they play a pivotal role in immune modulation and are described as important anti-oxidants. The combinations of vitamins with PUFAs will be explored later in this review.

Vitamin A, also known as retinol (Figure 2), is a vitamin obtained from the diet of animal origin as preformed vitamin A (dominantly retinol and retinyl esters) or from plant-derived foods as provitamin A (carotenoids). It has been estimated that preformed vitamin A is efficiently absorbed (70–90%). As the Average Requirement (AR) for vitamin A, 570 μg retinol equivalent (RE)/day for men and 490 μg RE/day for women are recommended by the European Food Safety Authority (EFSA) Panel on Dietetic Products, Nutrition and Allergies. Average vitamin A intake ranges between approximately 410-1080 μg RE/day in population < 18 years and between 820-1500 μg RE/day in adults when considering data obtained in nine EU countries [28]. Vitamin A is mostly known for being important in vision, with carrots as its main source. Besides carrots, vitamin A can also be obtained from fish, fruit, eggs, liver and margarine. Furthermore, it is important for normal functioning of the immune system. For example, vitamin A deficiency can cause malfunctioning of T-cells, neutrophils, NK-cells, monocytes/macrophages, Langerhans cells and B-cells, and acts on the production of several cytokines and growth factors, such as TNF-α, IFN-γ and IL-4 [29]. Furthermore, vitamin A metabolite retinoic acid (RA), which is converted by the enzyme retinaldehyde dehydrogenase (RALDH), has been described to play an important role in priming tolerogenic dendritic cells that generate regulatory T-cells (Treg) and stimulating IL-10 production by these cells [30].

The most important types of vitamin D are D₃ and D₂. For vitamin D₃, the greatest source is endogenous 7-dehydrocholesterol, generated in the liver from cholesterol, which can be converted by solar UVB radiation into vitamin D₃ (cholecalciferol) and further converted in the liver into 25-hydroxyvitamin D (calcidiol). This can either be stored in the liver or converted in the kidney into 1,25-dihydroxyvitamin D₃ (calcitriol), the active vitamin D₃ that can bind the vitamin D receptor (VDR) in cells. Besides endogenous generation of vitamin D₃, vitamin D₂ and D₃ can be obtained via the diet. Vitamin D₃ is present in fatty fish, dairy products and eggs. Vitamin D₃ cannot be produced in animals, but can for example be obtained by eating mushrooms or taking supplements. For
With increasing Th2 cell polarization, foods and supplements containing vitamin D, as well as sensible sun exposure. Similar to vitamin A, vitamin D can regulate the immune system by enhancing the antimicrobial activity of monocytes and macrophages, reducing antigen presentation by DCs and inhibiting proliferation and differentiation of B-cells and Th1 and Th17 cells, while promoting Th2 cells, thus suggesting a more anti-inflammatory effect [32]. Furthermore, vitamin D has been reported to induce Treg differentiation via instruction of tolerogenic DCs, much like vitamin A, and enhancing IL-10 production and downregulation maturation of DCs [33]. These similarities are not surprising, considering their nuclear receptor complexes (VDR/ retinoid X receptor (RXR) and retinoic acid receptor (RARα)/RXR), required for gene transcription, have been shown to interact [34]. For example, VDR can be repressed by RARα in leukaemia cells [55]. Hence, although it has been suggested that both vitamin A and D could be used to target autoimmune diseases and allergies, the interaction between these vitamins needs to be considered.

Vitamin E (α-tocopherol) is constituted by a trimethylated chromanol ring and a saturated phytyl side chain (Figure 2) and can be found in seeds and oils, such as sunflower oil, almonds and hazelnuts. For adults, an AI for α-tocopherol is set at 13 mg/day for men and 11 mg/day for women. Efficient α-tocopherol absorption requires the presence of fat, and it is estimated that the average α-tocopherol absorption from a usual diet is about 75% [36]. Opposite to vitamins A and D, vitamin E has not been directly linked to immune function, although it has been described to reduce the age-related decay of T-cells by inhibiting PGE2 production [37]. Furthermore, the most important feature of vitamin E is its anti-oxidant capacity. Of note, what makes vitamin E in particular of great interest is that it is located, alongside with PUFAs, into the membrane of lipid bilayer cells [38], and it this way can scavenge free radicals from PUFA in case of oxidation and protect from membrane damage due to lipid peroxidation.

5. Immunomodulation in allergy

**PUFAs**

**Clinical studies**

PUFAs are endowed with immunomodulatory properties. A small number of placebo controlled clinical trials studying the intake of fish oil during pregnancy or lactation report no statistically significant effects or positive effects on allergy development in the offspring. However, supplementation of fish oil starting early during pregnancy and continuing during breastfeeding was shown to reduce allergic sensitisation for food proteins in the offspring [39, 40]. Lower Th2 cytokine levels associated with IL-13 were measured in the plasma of these children [41]. Formula supplemented with AA and DHA, was also shown to prevent allergy development in young children compared to non-supplemented formula milk [42]. From epidemiological studies it is known that allergy is associated with low n-3 LCPUFAs, especially EPA and DHA, and high n-6 LCPUFAs in plasma or serum [43, 44], indicating a protective effect of n-3 LCPUFAs and the importance of aiming for an optimal ratio of n-3 over n-6 LCPUFA for immune development in neonates.

**In vivo studies**

Fish oils rich in n-3 LCPUFAs DHA and EPA have been found to modulate the function of dendritic cells and to suppress activation of T-cells [45, 46], and even have potential to prevent cow’s milk allergy in mice via the generation of Treg [47]. Furthermore, DHA-rich tuna oil was able to modulate the allergic response to whey and peanuts in sensitized mice [48]. In contrast, vegetable oil rich in n-6 PUFA LA has been reported to enhance the allergic reaction to cow’s milk by enhancing Th2 cell polarization, increasing mast cell degranulation and the allergic effector response [49]. By contrast, partial replacement of dietary intake of n-6 PUFA LA rich soybean oil with n-3 LCPUFA rich fish oil was found to reduce allergic sensitization and mucosal mast cell...
degranulation [48]. This supports the clinical reports where mainly n-3 LCPUFAs have been found to suppress allergic sensitization.

**In vitro studies**

PUFAs, when supplemented to (immune) cells, are incorporated into the cell membrane, thereby influencing cell properties [50]. For example, when incorporated into the CD4+ T-cell membrane, n-3 PUFAs can inhibit T-cell proliferation *in vitro* and *in vivo* [51-53]. In *in vitro* experiments, PUFAs are usually added in concentrations ranging from 2-100 μM [54-57] to study the effect on macrophages, mast cells, DCs, T-cells, or a combination of the latter two. Despite this variation, most papers report similar results. In macrophages, a downregulation of pro-inflammatory cytokines IL-1β, IL-6, IL-8 and TNF-α [58-60] and Reactive Oxygen Species (ROS) [55, 57] has been reported. The T-cell response instructed by DC is often observed to be downregulated [56], a decrease in secretion of pro-inflammatory cytokines TNF-α and IL-12 and upregulation of Treg cells has been reported [56, 61]. A reduction in histamine and leukotriene B4 levels have been shown when PUFAs (either n-3 alone or in varying ratios to n-6) were supplemented to mast cells [62, 63], while AA was able to activate intracellular ROS production and TNF-α release in mast cells [64]. AA is a component of the cyclooxygenase pathway in mast cells, and can be converted into prostaglandin H2 (PGH2). Both PGD2 and PGE2 are synthesized from PGH2, which are important in allergic symptoms by increasing vascular permeability and in maintaining the allergy through the activation of Th2 cells. In contrast, a lack of PGD2 has been reported to lead to mast cell hyperplasia, as shown in a PGD2 knockout mice with food allergy [65]. Finally, EPA and DHA have been shown to modulate inflammation by binding to several receptors, such as nuclear receptor PPARα/γ and GPR120 [66], and voltage-gated ion channels [67].

Taken together, these studies highlight the ability of n-3 LCPUFAs to reduce the inflammatory response by targeting multiple immune cells. Especially the suppression of Th2 cells and increase in Treg cells, and the decrease in histamine and/or PGD2 levels suggest that n-3 LCPUFAs may contribute to reduce the risk of allergy development and dampen allergic reactions. Targeting, both DCs/T-cells and mast cells, it can be speculated that n-3 LCPUFAs may have a protective effect in both the sensitization and effector response in food allergy, highlighting the potential of these PUFAs.

**Flavonoids**

As mentioned, flavonoids have been reported to possess anti-inflammatory properties as well. For example, pycnogenol has been used in a randomized double-blind controlled clinical treatment study, where a positive effect on allergic rhinitis symptoms was observed [68]. Pycnogenol is a French maritime pine bark extract containing a mixture of components (65-75% procyanidins), mostly used for medical purposes, but it can also be obtained from grape seeds and blue grape peels. The most important feature of this extract is its role as a strong anti-oxidant, which can control, for example, oxidative stress and NO production by macrophages [69]. With regards to food allergy, to our knowledge, no clinical trials have been performed using purified flavonoids. However, clinical trials using flavonoids are hard to be controlled, as flavonoids are present in nearly every form of nutrition.

**In vivo studies**

Flavonoids such as baicalin, quercetin and epicatechin have been tested in rat, mouse and guinea pig models via dietary intervention. All of these components were shown to have anti-allergic properties by preventing allergic sensitization. Effects include the reduction in IgE levels, lowering the amount of effector T-cells, increasing the amount of Treg cells and preventing DC maturation and, therefore, T-cell antigen presentation [70-74]. In contrast, one study also shows that quercetin, in a mouse model for egg allergy, increases Th2 levels and IL-1β and NO levels [75]. Mice received intraperitoneal (i.p.) injections on day 1 and 21 with either 25 or 50 mg/kg quercetin, and an i.p. injection with 20 μg Ova. By contrast, the other study which showed the preventive effect of
Supplementation of all vitamins has been incorporated into the diets of most households in the

Fat cell act in mice autophosphorylation level e.g. flavones and flavonols, are able to inhibit mast cell degranulation by inhibiting Syk cells such as mast cells pathways such as NFκβ and MAPK, causing the t

Th2 cells by stimulating the production of IL inflammatory processes reaction before cell viability is seriously affected and (superoxide O2, hydroxyl radical •OH and H2O2) resulting in synthesis and secretion of pro eicosanoids associated with their potential support in generation of Treg flavonoids also have anti-inflammatory effects associated with their anti-oxidant activity and inhibition of enzymes involved in the production of eicosanoids. Therefore, flavonoids have been proposed to be useful in allergy prevention Excessive reactive oxygen or reactive nitrogen species (ROS; RNS) produced in the process of oxidative metabolism as well as other inflammatory stimuli can initiate the inflammatory process resulting in synthesis and secretion of pro-inflammatory cytokines. By interaction with ROS (superoxide O2, hydroxyl radical •OH and H2O2) and RNS, flavonoids can terminate the chain reaction before cell viability is seriously affected and, therefore, they are able to modulate inflammatory processes [89, 90]. Importantly, ROS has been shown to enhance the differentiation to Th2 cells by stimulating the production of IL-4 through the activation of STAT6 and GATA3 as shown in a mouse model [91]. Furthermore, ROS is an important activator of cellular regulation pathways such as Nfkβ and MAPK, causing the transcription of pro-inflammatory genes such as TNF-α, IL1β, IL-6 and IL-8. In addition, flavonoids have also been shown to inhibit allergic effector cells such as mast cells known to contribute to allergic symptoms [84]. Certain groups of flavonoids, e.g. flavones and flavonols, are able to inhibit mast cell degranulation by inhibiting Syk at the autophosphorylation level [92, 93]. Syk is an essential signalling molecule in the FcεRI pathway, involved in cell degranulation. Inhibition of Syk has already been shown to reduce allergic asthma in mice [92].

Collectively, flavonoids have been shown to exhibit anti-allergic properties in vitro and/or in vivo, acting both on the sensitization phase, including inhibition of DC maturation and supporting Treg cell development, and the effector phase, including the inhibition of mast cell degranulation.

Fat-soluble vitamins

Clinical studies

Supplementation of all vitamins has been incorporated into the diets of most households in the
Western Society, especially concerning children, pregnant woman and the elderly. In relation to allergy, children with a history in respiratory allergies have been reported to benefit from vitamin A supplementation [94]. Furthermore, food allergy in children, especially cow’s milk allergy, has repeatedly been correlated to low vitamin D levels in plasma and serum [95-99], although one study in egg allergy did not demonstrate any correlation [100]. Vitamin D intake during pregnancy, however, did not correlate with a decrease of allergy in offspring [101], and even an increase has been reported [102]. Interestingly, it has been suggested that vitamin D deficiency is particularly correlated to food allergy in children with certain genotypes [103, 104]. Studies on the effect of vitamin E in food allergy are lacking.

**In vivo studies**

Vitamin A deficiency caused a break in oral tolerance through abnormally functioning DCs in the gut barrier, therefore inefficient antigen presentation and T-cell activation, which was rescued after vitamin A supplementation to the neonatal mice [105]. Mice with vitamin D deficiency show, in line with clinical data, a positive correlation with allergies [106]. Also in line with a clinical finding, egg allergy has been described to be enhanced by vitamin D deficiency [107], indicating a different mechanism driving this particular phenotype. This study reported a lower occurrence of Treg cells. By contrast, high supplementation of vitamin D in pregnant mice has also been reported to cause allergy due to a shift in the Th1/Th2 cell balance [108]. Other studies suggest that vitamin D is able to control IgE production through the vitamin D receptor in B-cells, therefore modulating allergic reactions [109, 110]. The many contradicting reports regarding vitamin D and its correlation to allergy show that the exact mechanisms behind food allergy and the role of vitamin D in the immune system is still to be elucidated.

**In vitro studies**

As mentioned before, retinoic acid (RA) can prime DCs to induce Treg cells. In the presence of RA, CD103 expressing DCs enhance the expression of RA converting enzyme RALDH2 which further facilitates the conversion of vitamin A derivate retinal to RA. In the mesenteric lymph nodes CD103 positive tolerogenic DC produce both RA and TGF-β which upregulate the expression of gut-homing integrin α4β7 and CCR9 in T-cells and stimulates Treg cell differentiation [30]. In allergy prevention, generation of IL-10 producing Treg cells is beneficial, as it downregulates the proliferation of Th2 cells.

Similar, vitamin D has also been reported in multiple studies to prime DCs that stimulate Treg differentiation and upregulation of IL-10 [33, 111, 112]. Furthermore, it has been shown to downregulate IL-12, Th1 cell proliferation and DC maturation markers CD40, CD80 and CD86 [112]. However, the mechanism behind this has not been reported so far.

Vitamin E has a principal role in defence against oxidant-induced membrane injury. This lipid soluble component is concentrated in the hydrophobic interior of cell membrane, and donates electron to peroxyl radical, preventing further reactions and consequent cell damage. It has been shown that supplementation with vitamin E decreases lipid peroxidation and superoxide (O₂⁻) production by impairing the assembly of nicotinamide adenine dinucleotide phosphate (reduced form) oxidase as well as by decreasing the expression of scavenger receptors (SR-A and CD36).

Also, it was observed that high dose vitamin E treatment decreases the release of pro-inflammatory cytokines such as IL-8 [113].

Collectively, fat-soluble vitamins A, D and E may mostly affect the sensitization phase in allergy, by binding influencing the function of DCs, B-cells and T-cells (vitamin A and D) or acting as a strong anti-oxidant (vitamin E) suppressing pro-inflammatory insults induced by oxidative stress.

**6. Combinations of components and their effects on allergy management**

The possible potential of certain foods to prevent allergy or inflammation has been extensively described. Mostly, PUFAs, flavonoids and micronutrients are suggested to be more effective against allergy when applied together in food. In many cases, in an integral food product, combinations of...
PUFAs, flavonoids and vitamins are present together. Additionally, minerals in food can be important in food allergy prevention as well. For example, food allergy in children has been associated with lower levels of zinc and selenium in their plasma [114, 115]. In vitro, zinc and selenium were reported to enhance Treg cell proliferation in allergen-stimulated cells [116] and decrease in PGD2 levels in mast cells [117]. Mediterranean food is an example of food containing multiple bioactive dietary components and frequently proposed to be beneficial for human health, as they contain fish and olive oil (rich in oleic acids and also contains PUFAs LA and a small amount of ALA), fruits (rich in vitamins and flavonoids) and wine (rich in flavonoids) [118]. Several studies have shown a positive correlation between the Mediterranean diet during pregnancy and a reduction of asthma and rhinitis [119-121]. Another popular source of flavonoids and micronutrients is cocoa from the cacao tree. In vivo, it has been shown to have immunomodulatory effects, including a decrease in IgE, TNF-α and IL-10 [122, 123]. Also other common foods such as apple extract (rich in vitamins and flavonoids), rooibos tea and adlay bran (both rich in flavonoids) have been associated with a decrease in pro-inflammatory cytokines and the allergic response, mainly through the lowering of the production of pro-inflammatory cytokines, IL-4, IL-6 and Th2 cells. In addition, walnut polyphenolic components have been described to decrease TNF-α and peripheral blood mononuclear cell (PMBC) proliferation, although it induces a shift towards Th2 cells [124, 125]. It, however, does contain important anti-oxidant properties.

PUFAs alone are highly susceptible to lipid oxidation. Several studies report the protective antioxidative effect of different flavonoids on PUFAs [126-129]. Some vitamins have been described to exhibit a similar effect [130-132]. Vitamin E resides in the membrane lipid bilayer cells, like PUFAs [38], leading to membrane stabilization and protection against lipoxidation. The importance of this has been highlighted in a review by Raederstorff et al [133], stating that the intake of PUFAs is directly linked to the vitamin E requirement. Therefore, they recommend a dose of vitamin E between 12-20 mg/day based on the amount of PUFAs in an average Western diet. Additionally, the use of flavonoids to protect PUFAs from lipid oxidation has been proposed in previous research, where they even introduce PUFA-flavonoid hybrids or conjugates [126, 134].

Conclusion

A summary of the known effects of PUFAs, certain flavonoids and vitamins A, D and E on the allergic sensitization and effector response in food allergy can be found in Figure 4. n-3 LCPUFAs have promising anti-inflammatory and anti-allergic properties, they may act on both the sensitization as well as the effector phase of food allergy and clinical intervention studies have shown some promising allergy protective effects. However, due to their high susceptibility to lipid oxidation, supplementation of n-3 LCPUFA in combination with anti-oxidants, with a preference for vitamin E to scavenge lipid radicals in the cell membrane and thereby protecting against damage caused by lipid peroxidation, is indicated. Flavonoids such as pycnogenol or quercetin are also suitable as anti-oxidants, contain anti-inflammatory properties and may be able to induce Treg cell differentiation. The latter is also known for vitamin A and D. Like n-3 LCPUFAs, flavonoids may also act on both the sensitization and effector phase, while for vitamin A and D appropriate levels are required for proper Treg induction to avoid allergic sensitization. Future studies are needed to reveal the food allergy protective properties of combined supplementation with n-3 LCPUFA, certain vitamins and flavonoids for prevention purposes and possibly also for symptom relieve.
Figure 4: The effect of PUFAs, flavonoids and vitamins on food allergy. The colour of the arrows and text indicate if the evidence is obtained from clinical, in vivo or in vitro data. The + or – indicates if the observed effect is an inhibitory or stimulatory response of a certain cell type. Note that clinical and in vivo arrows indicate the observed end stage effects only, this may not be a reflection of the direct effect of PUFAs, flavonoids and vitamins on the target cells. Therefore, the components could actually target a cell group earlier in the pathway.
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References


