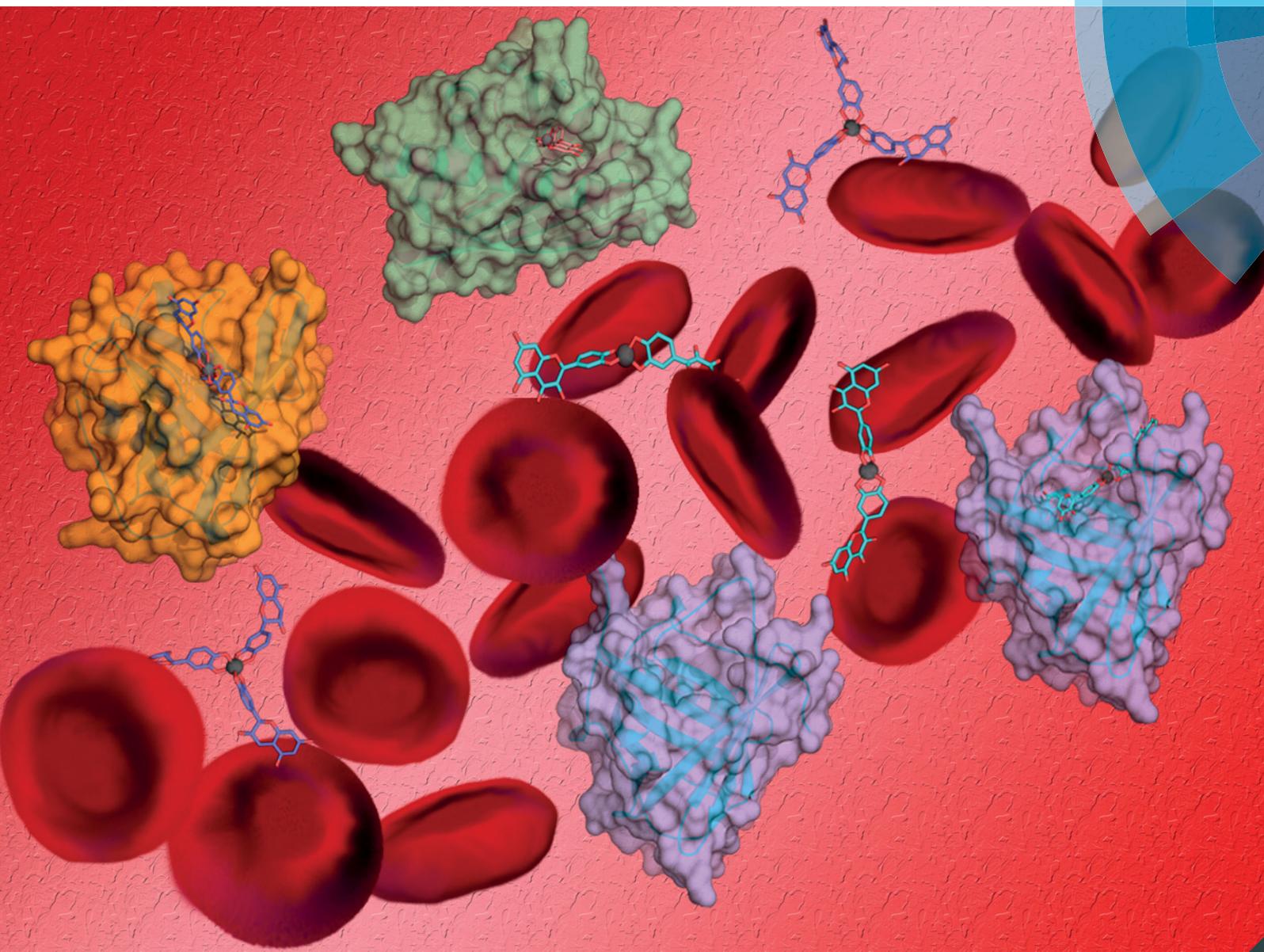


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Linking iron-deficiency with allergy: role of molecular allergens and the microbiome

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Atopic individuals tend to develop a Th2 dominant immune response, resulting in hyperresponsiveness to harmless antigens, termed allergens. In the last decade, epidemiological studies have emerged that connected allergy with a deficient iron-status. Immune activation under iron-deficient conditions results in the expansion of Th2-, but not Th1 cells, can induce class-switching in B-cells and hampers the proper activation of M2, but not M1 macrophages. Moreover, many allergens, in particular with the lipocalin and lipocalin-like folds, seem to be capable of binding iron indirectly *via* siderophores harboring catechol moieties. The resulting locally restricted iron-deficiency may then lead during immune activation to the generation of Th2-cells and thus prepare for allergic sensitization. Moreover, iron-chelators seem to also influence clinical reactivity: mast cells accumulate iron before degranulation and seem to respond differently depending on the type of the encountered siderophore. Whereas deferoxamine triggers degranulation of connective tissue-type mast cells, catechol-based siderophores reduce activation and degranulation and improve clinical symptoms. Considering the complex interplay of iron, siderophores and immune molecules, it remains to be determined whether iron-deficiencies are the cause or the result of allergy.

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Introduction

Iron is an essential nutrient utilized in almost every aspect of normal cell function. All cells require iron to proliferate, iron being essential for DNA biosynthesis, protein function and cell cycle progression. In humans, iron is critical for a wide variety of biological processes as it allows transportation of oxygen, aids in the energy household and is essential for a healthy immune system.



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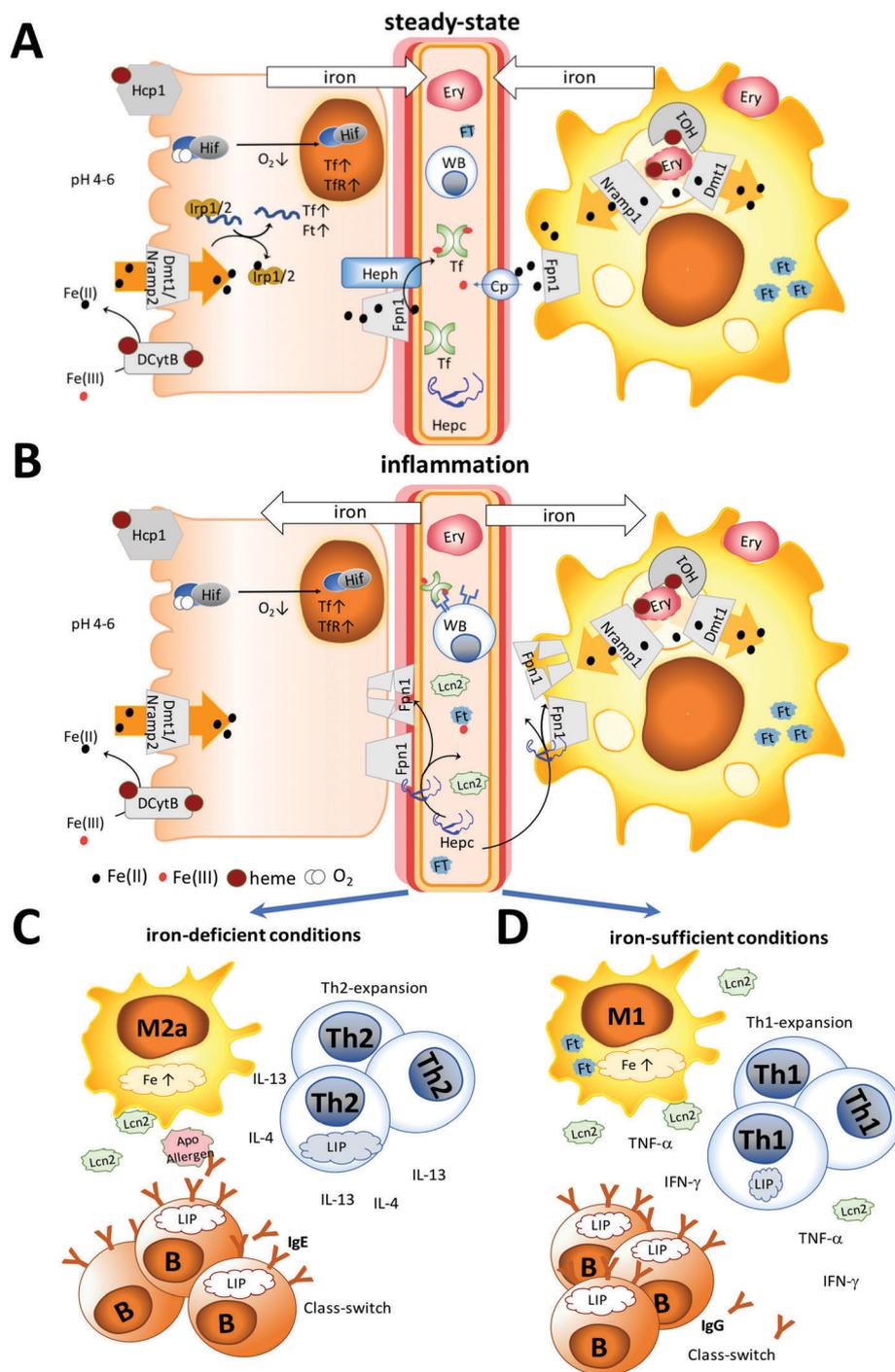


Fig. 1 Iron homeostasis under steady-state and inflammation. (A) Under steady-state conditions, dietary iron absorption occurs *via* (1) the divalent metal-ion transporter 1 (Dmt1) upon reduction of ferric iron in its ferrous form by ascorbic acid or duodenal cytochrome *b* (Dcytb) and (2) the heme transporter (Hcp1) in the form of heme. Iron is released into the circulation by (3) macrophages recycling senescent erythrocytes with the help of heme oxygenase 1 (HO1) and dietary iron by enterocytes *via* the iron-exporter ferroportin (Fpn1) in the form of Fe(II). Subsequently, ceruloplasmin (Cp) or membrane-bound hephaestin (Heph) oxidizes iron to Fe(III) for transport *via* transferrin (Tf). Intracellularly iron concentrations are regulated by the iron regulatory proteins (Irp)1/2. Binding of these proteins to iron results in the transcription of transferrin and ferritin (Ft). Also, a decrease of oxygen can activate hypoxia-inducible factor (Hif), leading to transcription of Tf and the transferrin receptor (TfR). (B) Under inflammation, not only hepcidin (Hepc), but also innate proteins like lipocalin 2 (Lcn2) and ferritin are released into the circulation, Hepc binding to ferroportin (Fpn1), thereby initiating its degradation and leading to cytoplasmic accumulation of iron. The immune response differs depending on the human's iron status. (C) Under limited iron supply Th2-, but not Th1-cells, will expand due to their larger intracellular iron pool and secrete IL-4 and IL-13. M2 macrophages will differentiate into an allergic subtype, further providing a Th2 environment. B cells expand *via* transferrin receptor-independent mechanisms and induce class-switching in the presence of IL-4 and IL-13 towards IgE. Apo-allergens may cause local iron-deprivation or interfere with the regulatory functions of Lcn2 and further modulate the immune-activation. (D) In contrast, under sufficient iron-supply, macrophages may release Lcn2, Th1 cells will expand, secreting IFN- γ and TNF- α , and B cells will generate IgG antibodies.



in an increase in the dietary iron absorption. Intracellular iron is also regulated by iron regulatory proteins (IRPs) 1 and 2 with iron-responsive elements, in which upregulation of these proteins reflects low body iron stores and an increase of dietary iron absorption.⁴³ Moreover, oxygen can regulate iron homeostasis. During hypoxia, the hypoxia-inducible factors (HIF) can target genes encoding transferrin and the transferrin receptor, leading to increased expression of transferrin and thus increased transport of ferric iron into cells.⁴⁴

Non-transferrin bound iron and the labile iron pool

Excreted iron is usually bound to transferrin, ferritin or heme. In the circulation, also non-transferrin-bound iron, NTBI, is present, which represents a heterogeneous population that comprises organic anions with low affinity to iron (*e.g.* citrate, phosphates and carboxylates), polyfunctional ligands (chelates, siderophores and polypeptides), albumin⁴⁵ and surface components of membranes (*e.g.* glycans and sulfonates) able to bind Fe(II) and Fe(III). The NTBI is typically present in concentrations up to 10 μM and its existence has been correlated with high levels of transferrin saturation. Similarly, intracellularly, this heterogeneous population of redox-active Fe complexes is called the labile iron pool, LIP. In cells, the iron concentration usually ranges from 20 to 100 μM and is largely associated with proteins, whereas only a minor fraction of the cellular iron is present as the LIP (> 1%, up to 5 μM)⁴⁶. In the cytosol, Fe(II) is prevalent, with glutathione probably acting as a major buffer. The LIP is primarily found in erythroid and myeloid cells, as well as in neuronal cells.

Importantly, though the NTBI or LIP represents only a fraction of the total intra- and extracellular iron, fine-tuning the LIP-levels has physiologically and immunologically wide-reaching consequences. Both iron forms are the immediate therapeutic targets of diseases associated with a misbalance in the iron homeostasis, *e.g.* hereditary hemochromatosis, myelodysplastic syndromes and sickle-cell disease.⁴⁷

The immune system

The immune system and iron

Iron is essential for many peroxide- and nitrous oxide-generating enzymes,⁴⁸ and regulates cell growth, cell differentiation, and cytokine production. Iron can activate protein kinase C, which leads to phosphorylation of compounds regulating cell proliferation. In addition, iron is necessary for myeloperoxidase activity to form hydroxyl radicals, enabling neutrophils to efficiently eliminate bacteria.⁴⁹ Thus, any misbalance in the iron homeostasis towards either deficiency or overload has wide-reaching immunological consequences.

Macrophages are immune cells known to store iron. The reason for the high presence of iron in macrophages is their pivotal role in systemic iron recycling, where senescent erythrocytes are cleared by predominantly splenic macrophages.⁵⁰ In addition to their important role in erythrocyte clearance and maintenance, their anti-inflammatory or inflammatory state

seems to be dependent on the iron content. Anti-inflammatory macrophages have a lower iron-content and an increased expression of proteins associated with iron efflux and can be discriminated from inflammatory macrophages, which harbour high iron-levels.⁵¹ Macrophage phagocytosis is generally unaffected by iron deficiency, even though macrophage bactericidal activity is affected.⁴⁸ Neutrophils under iron-limited conditions show impaired or lower killing activity due to the reduced activity of myeloperoxidase and reduced mobility to inflamed sites. Likewise, NK-cells exhibit lower activity due to reduced differentiation and proliferation under iron-restricted conditions. Importantly, T lymphocytes can also actively modulate the NTBI pool by uptake and export, with T cell deficiency associated with an accumulation of iron in the liver and pancreas.⁵² Impaired iron-uptake *via* transferrin receptor 1 (TfR1) caused by mutations can result in severe B- and T-cell deficiencies due to the lack of activation, which can partly be compensated through the internalization of iron *via* NTBI-pathways.⁵³

Allergy and iron

Allergy is an immune-mediated disease, caused by an aberrant immune response towards exogenous, normally harmless antigens derived from pollen, house dust mites, animal dander, insect venom and food components. In particular, in the westernized world the prevalence of allergy seems to increase, with almost 20% of the adults in Germany having at least one self-reported doctor diagnosed allergy.⁵⁴ Also in the United States, the prevalence of respiratory allergies is approximately 20%, whereas the prevalence of food allergies has increased from 3 to 5% and the prevalence of skin allergies from 7 to 12%.⁵⁵ Allergy defined as type I hypersensitivity causes an immediate reaction usually within minutes upon re-exposure to the antigen in an individual with preformed antigen-specific IgE antibodies. Allergic symptoms may affect the eyes, nose, skin, the lungs or the gastrointestinal tract, leading to red eyes, an itchy rash, runny nose, shortness of breath, swelling or diarrhea. In severe cases, a systemic reaction can occur, resulting in an anaphylactic shock.

Mechanistically, it is important to note that the presence of specific IgE antibodies, referred to as allergic sensitization, is a precondition of allergic symptoms. They are a product from plasma cells when stimulated by T-helper 2 cell (Th2-) cytokines IL-4 and IL-13. A Th2 bias in the immune response is typically associated with allergies. Re-exposure to the allergen results in binding and cross-linking of IgE antibodies bound *via* high-affinity receptors on effector cells. Mast cells then discharge their granules containing histamine, leukotrienes and other active agents by exocytosis, causing allergic reactions.⁵⁶ However, many people may just be sensitized, thus already having IgE-antibodies, but not yet an allergic reaction upon exposure to the respective allergen.⁵⁴

As such, the events leading to the initiation of IgE formation are poorly understood, though it is generally accepted that the shift in the immune balance towards Th2 directly correlates with the overproduction of allergen-specific IgE.



Epidemiological and experimental evidence

Iron and allergy. The poor iron status at birth was associated with an increased risk of developing allergic diseases.⁵⁷ It has been argued that a massive perinatal lymphocyte expansion may have led to a prioritization of erythrocytes at the expense of other vital developing tissues⁵⁸ due to the restricted iron supply.⁵⁷ This may then have compromised vulnerable Th1 lymphocytes having lower intracellular iron stores and may have promoted eosinophilia. Accordingly, when the maternal iron status during pregnancy was reduced, this was adversely associated with childhood wheezing, altered lung function and atopic sensitisation in the first 10 years of life.⁵⁹

Along with a lower iron status increasing the risk of atopy, high iron concentration in umbilical cord samples was associated with a decreased risk of wheezing and eczema in the population-based Avon Longitudinal Study of Parents and Children.⁶⁰ Similarly, in a British study decreased serum ferritin levels were found in children with atopic eczema.⁶¹ The lower iron-status is a consistent and a reproducible finding in multiple US cohorts, which clearly associates atopy with anemia.⁵ Also in a case-controlled, population-based Korean study, low beta-carotene, iron, folic acid, and dietary vitamin E were associated with atopic dermatitis in young children.⁶² Another study showed a greatly reduced incidence of wheezing and asthma in infants of mothers who were supplemented during pregnancy with vitamin C, a known contributor to increasing iron bioavailability.⁶³ The change in the iron status impacted allergy also *in vivo* in a murine model of allergic asthma, in which oral iron supplementation, as well as systemic iron administration, suppressed airway manifestations.⁶⁴

Misregulated iron-metabolism can affect atopy or the generation of allergies. Patients with a much too high iron load due to frequent blood transfusions have a decreased CD4/CD8 ratio,^{65,66} and their increased serum ferritin levels significantly correlate with the number of transfusions.

More female allergy sufferers: association with iron?

Finally, as iron homeostasis differs between the genders⁶⁷ and before and after adolescence, it may contribute to the differences seen in the prevalence of allergy in the various groups. During childhood, boys are more affected by allergy than girls, but this changes in adulthood and women are more likely to be affected than men. In a German evaluation, 24% of men, but 35% of women suffer from at least one allergy and 2.9% of men, but 6.4% of women suffer from food allergies.⁶⁸ Over 20% of Portuguese women were found iron-deficient and other studies have also confirmed that females present more often iron deficiency.^{69,70}

All in all, there is consistent evidence that the iron-status of allergic subjects is reduced and may be linked with the disease.

Iron and cancer. It should be considered that cancer is in general associated with a highly suppressed immune defense (tumor tolerance phenomenon) and thus cancer and allergy have opposite immunological features.⁷¹ In fact, epidemiological studies have suggested that an inverse association between

allergic diseases and cancer exists, indicating that allergic and/or atopic subjects with elevated IgE levels have a higher risk for allergies, but a lower risk of developing certain cancer types.⁷² As far as the iron content is concerned, while decreased iron levels predispose to allergies, increased serum iron correlates with an increased cancer risk.^{73–78}

Therefore, iron levels affect in opposite ways the immune regulation in allergy and cancer.

Immune effects of iron

Iron deficiency affects more Th1 than Th2 immune cells.

The proliferative phase of T-cells is dependent on iron supply. Activation of T cells leads to the expression of TfR *via* an IL2-dependent pathway, which facilitates iron uptake. The iron availability is known to differentially modulate the proliferation of different Th cell subsets. Th1 cells usually associated with inflammation have a lower labile iron pool and activation of Th1 cells can be readily blocked⁷⁹ by inhibiting iron-uptake *via* TfR and/or deferoxamine, whereas Th2 cells seem to maintain a larger amount of iron in an assumable less labile and less readily chelatable pool that is only partly affected by blocking TfR and/or deferoxamine.⁸⁰ As such, under iron-restricted conditions, DNA synthesis in Th1, but not Th2 cells, was inhibited. In line with these experiments, the Th1-associated cytokines IFN- γ and the IL-12/IL-18 mediated proliferation was found to be severely affected by iron chelators, whereas Th2-associated cytokines IL-13, which is IL-4 mediated, were resistant to potent iron chelators.⁸¹

Thus, it is very likely that under conditions of lymphocyte expansion the limited iron supply in allergic subjects will favour the development of a Th2-environment, thereby preparing for later allergic sensitisation.

M2 macrophages are more susceptible to iron-deprivation.

Classical activated M1 macrophages are characterized by secretion of inflammatory cytokines, harbour high iron-levels⁵¹ and are important contributors to the classical Th1 response. In contrast, alternative activated M2 macrophages usually residing in the tissues have immunoregulatory functions, have a lower iron-content and participate in Th2 reactions and in wound healing processes.

Corna *et al.* demonstrated that under iron deprivation by deferoxamine both M1 and M2 macrophages enhanced IRP1 activity, whereas IRP2 was more strongly enhanced in M2 macrophages.⁸² Deferoxamine treatment also does not lead to the suppression of ferritin heavy chain expression in M1 macrophages, indicating high enough iron stores, whereas in M2 macrophages TfR1 was upregulated for continuous iron supply.⁵¹ As such, M1 macrophages are not as affected by iron-deficient conditions as M2 macrophages. Importantly, M2 cells are not as efficient in expressing molecules involved in antigen presentation, such as MHC class II (I-Ab), or the costimulatory molecule CD86 after T-cell stimulation under iron-deficient conditions, whereas M1 macrophages seem unaffected by iron chelators.

Iron suppresses class-switching in B-cells. Resting B-cells express much lower levels of TfR on the plasma membrane than on T-cells⁸³ and seem to have evolved also transferrin-independent



and apigenin⁹⁹ inhibited airway inflammation. In double-blind placebo controlled clinical trials, *O*-methylated catechins reduced symptoms of Japanese cedar pollinosis¹⁰⁰ and catechins also reduced symptoms in mild and moderate atopic dermatitis.¹⁰¹ From this, it becomes apparent that iron levels and chelators are able to regulate mast cells and thus have an impact on the severeness of allergic symptoms.

Allergens

Structure–function relationships: role for siderophores and iron. One of the fundamental riddles in allergy is why certain proteins emerge as allergens. It is assumed that they are directly related to the critical events triggering the Th2 bias. Despite the existence of thousands of protein families, the structures of major allergens can be restricted to few protein families. Although many allergens have been characterized in terms of secondary and tertiary structures, it is still uncertain whether common structural, functional or biochemical features underlie their ability to generate an allergic response.

Nearly all major allergens from mammals belong to the lipocalin family,¹⁰² while plant allergens usually originate from

the prolamin (2S albumin, lipid binding proteins (LTPs)) and cupin (7S, 11S) superfamilies or from the pathogenesis-related (PR)-10 family.¹⁰³ All members of these families share certain characteristics like their great structural stability and their ability to serve as carriers for a variety of compounds with lipidic segments.^{104,105}

Allergens deriving from mammalian sources usually belong to the lipocalin family. Lipocalins show unusually low levels of overall sequence conservation with pairwise sequence identities often below 20%. Nevertheless, as illustrated in Fig. 3 the lipocalin fold is highly conserved.¹⁰⁶ This β -barrel structure shapes a calyx-like site which gives the name to the protein family and is the main feature regarding the binding abilities of the lipocalin fold.¹⁰⁷ While the wider end of the barrel is open to the solvent and rich in polar and charged amino acids, the narrower end is an inner, buried region rich in hydrophobic amino acids. Loops flanking the calyx display a great sequence variability that endows lipocalins with the ability to bind a large variety of ligands having polar and non-polar moieties. This property has been exploited in protein design that uses lipocalins as scaffolds to engineer novel binding proteins (“anticalins”).¹⁰⁸

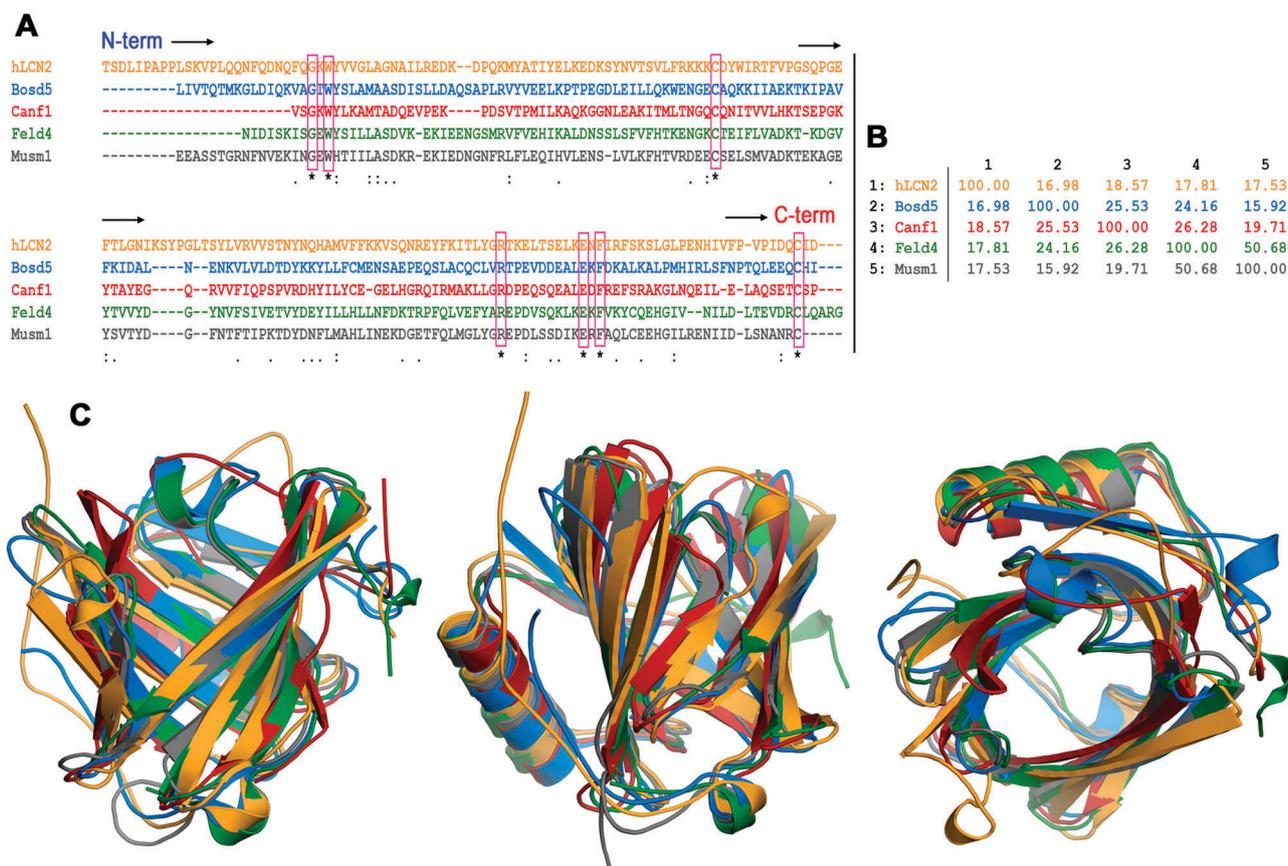


Fig. 3 Sequence and structural alignment of lipocalins. (A) Clustal multiple sequence alignment of the following lipocalins. hLcn2: human Lcn2, Bos d 5: bovine β -lactoglobulin, Can f 1: dog allergen, Fel d 4: cat allergen, and Mus m 1: pheromone binding rodent major urinary protein from a mouse. The seven residues strictly conserved are boxed. (B) Percent identity matrix for the multiple sequence alignment in A. (C) Three views of the structural superposition of the hLcn2 (orange) crystal structure PDB id 1i6 m, Bos d 5 (blue) crystal structure PDB id 3NPO, Can f 1 (red) and Fel d 4 (green) homology model structures (ref. 100), and Mus m 1 (gray) crystal structure PDB id 1MUP. The percentages of allergen residues and RMSD values for backbone atoms in the structural superposition with hLcn2 are the following – Bos d 5: 67%, 1.362 Å; Can f 1: 66%, 1.574 Å; Fel d 4: 68%, 1.235 Å; Mus m 1: 73%, 1.158 Å.



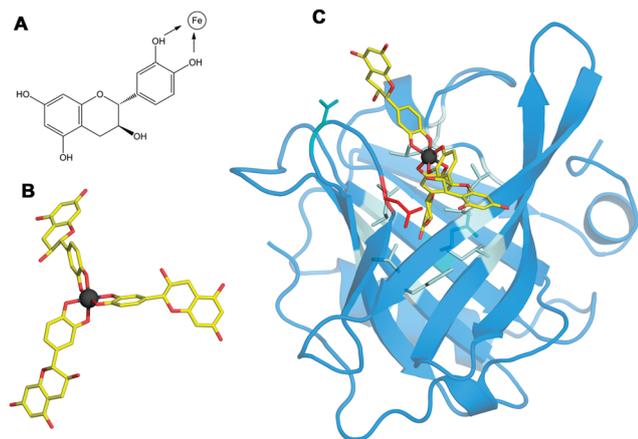


Fig. 4 Structure of the Bos d 5-Fe(catechin)₃ complex. (A) The structural formula of catechin. Catechol hydroxyls participating in the chelation of iron are marked with arrows. (B) 3D structure of the Fe(catechin)₃ ligand showing the spatial arrangement of catechols to set the hexadentate octahedral coordination of iron (carbons in yellow, oxygen in red, and iron in dark gray). (C) 3D structure of the Bos d 5-Fe(catechin)₃ complex showing the location of the ligand at the calyx of the lipocalin. Residues within a 3.5 Å distance from the ligand are displayed as sticks with the following color code: nine non-polar in pale cyan, two polar in cyan and one acidic in red.

Lipocalins are usually secreted and can be found in the dander, urine, fur, and saliva of animals.¹⁰⁹ They have been described as powerful bacteriostatic agents against various microorganisms, by impeding their iron sequestration and binding to siderophore-iron complexes,^{110,111} but in accordance with their ligand binding plasticity, lipocalins also seem to act as carriers for lipids and hormones.

The human homologue lipocalin 2 (Lcn2, NGAL) has immune-regulatory function, but is also a growth factor¹¹² and a stress protein that is released under various inflammatory conditions and in cancer.¹¹³ The binding of Lcn2 to bacterial siderophores, which are low molecular weight compounds that are amongst the strongest soluble Fe(III) binding agents known, is considered a key feature against bacterial infections. Secreted Lcn2 seems to have specialized towards siderophores with catechol-moieties that facilitate their binding in the calyx site (see Fig. 4).¹¹⁴ Moreover, Lcn2 has been described to bind to endogenous siderophores like 2,5-dihydroxybenzoic acid (2,5-DHBA),¹¹⁵ thereby probably ensuring that excess free iron does not accumulate in the cytoplasm. Mammalian cells lacking this endogenous siderophore accumulate abnormally high levels of intracellular iron, leading to high levels of reactive oxygen species.¹¹⁵

Siderophores and iron modulate the Th2-potency of allergens.

As iron is essential for almost all life, microbes and plants have evolved efficient iron sequestration strategies by producing siderophores that usually form a stable, hexadentate, octahedral complex predominantly with Fe(III).¹¹⁶ Siderophores are usually classified by the ligands used to chelate the ferric iron with the major types of siderophores having catechol, hydroxamate or α -hydroxycarboxylate moieties, as depicted in Fig. 2. Also, combinations of the chemical groups are possible with microbes often employing non-ribosomal peptides to act as siderophores.¹¹⁷

Importantly, also many fruits and plants feature the presence of polyphenols/flavonoids known to behave as high-affinity iron chelators, a fact that is commonly overlooked,³⁴ but that may contribute to their mast cell stabilizing ability. In addition, the ability of those compounds to chelate iron has been proposed to be a key element in their anti-oxidant properties.¹¹⁸

With regard to allergy, there seems to exist a particular role for catechol-type siderophores, which may also be related to the fact that catechol groups chelate iron^{119,120} at physiologically relevant pHs.

In this respect, it is relevant that lipocalin 2 can bind to only catechol-containing siderophores and not to others. This is an important characteristic that also seems to be extendable to many major allergens. Many lipocalin allergens such as the major milk allergen Bos d 5, or the major birch allergen Bet v 1, a prototype for the PR-10 protein family with a lipocalin-like architecture, are capable of transporting iron *via* catechol-type siderophores.^{121,122} Importantly, their loading state, apo- (empty) or holo- (filled), seemed to be decisive for the subsequent immune response. Apo-allergens can mount a Th2-response *in vitro*, whereas the holo forms are rather immune-suppressive, indicating that the iron-carrying form impedes allergic sensitization.^{121,122}

As such, the natural ligand of the major birch pollen allergen Bet v 1 has been identified to be the flavonoid quercetin-3-O-sophoroside;¹²³ the major peanut allergens Ara h 2 and Ara h 6, belonging to the 2S family, bind the flavonoid epigallocatechin-3-gallate;¹²⁴ the major peanut allergen Ara h 1 from the 7S family forms large complexes by binding proanthocyanidins, which are oligomers consisting of catechin and epicatechin and their gallic acid esters.¹²⁵ Accordingly, the pathogenesis-related PR-10 proteins and major allergens in strawberries, Fra a 1 and Fra a 3, have been crystallized with catechin ligands.¹²⁶

In summary, there is solid evidence that allergens are capable of binding in particular catechol-type structures like quercetin and rutin with high iron affinities that surpass iron-affinity constants of deferoxamine.^{127,128}

Importantly, a great number of these polyphenols have been described in the literature to exhibit anti-allergic properties. Taking lipocalins as an example, allergens are not only structurally at the border between self and non-self, but may also functionally interfere with the human immune-regulatory processes.

How normally harmless antigens become allergens with their characteristic Th2 skewing capacity is not known. There are several possible scenarios: (i) iron deficiency turns holo-lipocalins into apo-allergens, or (ii) exogenous lipocalins enter the body already devoid of a ligand in their calyx. In this case, they – due to their high affinity – will immediately sequester endogenous siderophores or comparable ligands directly at the mucosal sites, thereby contributing locally to an iron-deficient state. Additional triggers then may activate lymphocytes to become Th2 rather than Th1 cells.^{121,122,128} (iii) Allergenic lipocalins may in an ongoing immune response interfere with the function of Lcn2, *e.g.* during infections either by providing or by sequestering ligands for Lcn2. In any of these cases,



the immune function of Lcn2 may be skewed by allergens towards Th2.

Can microbiota interfere with iron homeostasis?

From hygiene hypothesis to colonizing microbiota. The so-called hygiene hypothesis originated from observations that hay fever is more common in small families having few members than in large families and is associated with a less “dirty” environment, hence less microbial exposure.¹²⁹ Moreover, living on a farm protects against atopy, hay fever, and asthma, especially in children.¹³⁰ As such, cumulative evidence suggests that decreased exposure to microorganisms promotes allergy. The microbiota that colonizes humans has not merely a commensal, but rather a mutualistic relationship with their human host. It is accepted today that as such the bacterial composition has a profound impact on the immune system and *vice versa*.

Facts on microbiota in healthy versus allergic subjects. In the human healthy gut over 1000 bacterial species have been described,¹³¹ with an individual having at least 160 species, of which 52 species account for over 90%.¹³² Aerobic organisms including *Streptococci* and *Lactobacilli*, occasionally with *Candida* spp., predominantly colonize the human stomach, duodenum,

and proximal jejunum,¹³³ whereas an anaerobic predominance prevails in the distal ileum and colon. Dominant colonic organisms in humans include *Clostridium* spp., *Bacteroides* and *Bifidobacterium*.¹³³ Thus, the *Firmicutes* and *Proteobacteria* phyla predominate in the duodenum, whereas *Firmicutes* and *Bacteroidetes* are the predominant phyla in the distal colon.

Microbiome depletion as a result of broad-spectrum antibiotic treatment led not only to anaemia and thrombocytosis but also to an altered immune homeostasis, resulting in diminished granulocytes and B cells¹¹⁶ in the bone marrow and increased CD8⁺ T-cells in mice. Importantly, faecal microbiota transfer partly rescued these hematopoietic changes.¹³⁴ In rats inoculated with human faecal microbiota, provision of an iron-fortified diet after feeding an iron-deficient diet significantly increased the abundance of dominant bacterial groups such as *Bacteroides* spp. and *Clostridium* cluster IV members compared with rats on an iron-deficient diet only. Moreover, iron supplementation increased the gut microbial butyrate concentration 6-fold compared with iron depletion and did not affect histological colitis scores, suggesting that iron supplementation enhanced the concentration of beneficial gut microbiota metabolites and may contribute to gut health.¹³⁵

Table 1 Organisms in the human microbiota associated with allergy

Phylum	Family	Genus	Siderophore use	Reported abundancy in allergy	
Actinobacteria ¹³⁷	Bifidobacteriaceae ^{136,140,141}	<i>Bifidobacterium</i> ¹⁴⁰	+/-, Fe(II)	Increased ¹⁴⁰ / decreased ^{136-138,141}	
	Coriobacteriaceae ¹⁴⁰	<i>Collinsella</i> ¹⁴⁰	+	Increased ¹⁴⁰ / decreased ^{137,141}	
Bacteroidetes ^{137,140,142}	Bacteroidaceae	<i>Bacteroides</i>	+/hr	Decreased ^{137,140,141} /increased ¹⁴³	
	Rikenellaceae	<i>Rickenella</i>	+/heme	Decreased ¹⁴¹	
	Porphyromonadaceae	<i>Porphyromonas</i> <i>Parabacteroides</i> ¹⁴⁰	Fe(II)/heme ?	Decreased ^{140,141}	
	Prevotellaceae	<i>Prevotella</i>	+, heme, tr -	Decreased ^{140,141,143} /increased ¹⁴⁴	
Firmicutes	Lactobacillaceae	<i>Lactobacillus</i> ^{140,141}	-/Mn	Increased ¹⁴⁰ / decreased ¹⁴¹	
	Streptococcaceae	<i>Streptococcus</i> ¹⁴⁰	+, fr, lr, heme, hr	Decreased ^{138,140,141}	
	Enterococcaceae	<i>Enterococcus</i>	+, heme	Decreased ¹³⁸ /increased ^{140,141}	
	Staphylococcaceae	<i>Staphylococcus</i>	+	Decreased ^{138,145}	
	Clostridiaceae/cluster I ^{140,141}	<i>Clostridium</i>	+, heme	Increased ^{136,137,141}	
	Clostridiaceae/cluster IV ^{140,141}	<i>Butyricoccus</i> <i>Anaerobacter</i> ¹⁴⁰	? ?	n/a Increased ^{137,140} / decreased ¹³⁹	
	Lachnospiraceae ^{138,140,143,146,147}	<i>Lactonifactor</i> <i>Blautia</i> <i>Roseburia</i>	? + +	n/a Decreased ¹⁴³ / increased ¹³⁸ Increased ^{138,140,141}	
	Ruminococcaceae/cluster IV ^{140,143}	<i>Ruminococcus</i> <i>Faecalibacterium</i> <i>Subdoligranulum</i>	+ + Fe(II)	Increased ^{138,140} / decreased ^{139,141,143} Increased ^{138,140} / decreased ^{141,143}	
	Veillonellaceae	<i>Dialister</i> ¹⁴¹ <i>Megamonas</i> <i>Megasphaera</i> ¹⁴¹ <i>Veillonella</i> ¹⁴⁰	+ + + +	Decreased ¹⁴¹ n/a Decreased ¹⁴¹ Decreased ^{140,141}	
	Proteobacteria ¹³⁷	Enterobacteriaceae ¹³⁹	<i>Escherichia</i> <i>Citrobacter</i>	+ +	Decreased ¹³⁸ /increased ^{137,139} Increased ¹³⁹
		Pseudomonadaceae	<i>Pseudomonas</i>	+	
		Moraxellaceae	<i>Acinetobacter</i> ¹⁴⁴	+ ¹⁴⁸	Decreased ¹⁴⁴
		Campylobacteraceae	<i>Campylobacter</i> ¹⁴⁹ <i>Arcobacter</i>	+ +	Decreased ¹⁵⁰
Verrucomicrobia	Akkermansiaceae ¹⁴⁰	<i>Akkermansia</i>	+	Increased ¹⁴⁰ / decreased ^{139,141}	
Kingdom Fungi: Ascomycota	Saccharomycetaceae	<i>Candida</i>	+	Increased ¹⁴¹	

Code: predominantly found in colon (bold face), upper G/I (regular font). Ferritin – fr, transferrin – tr, lactoferrin – lr, hemophores – hr.



Importantly, microbes able to inhabit the upper G/I tract seemed to be reduced in allergic subjects compared to non-allergic subjects.

There are only a few studies on the microbiota conducted in humans. As such, food allergic patients seem to have an increased abundance of bacteria of the order *Clostridiales* (*Lachnospiraceae*, *Ruminococcaceae*)^{136–139} and a decreased abundance of the order *Bacteroidales*.^{136,140,141}

Microbiota interfere with iron levels via siderophores. An interesting aspect here is that *Proteobacteria*, *Bacteroidetes* and some family members of *Firmicutes* (see Table 1) are more likely to influence dietary iron uptake in the host due to the fact that their site of residency coincides with the site of iron-uptake. When screening these bacteria for their ability to secrete or utilize siderophores, it is apparent that indeed most of these organisms can acquire iron by siderophore-mediated mechanisms. As no data indicated the increased or decreased abundance of certain bacterial order, one can only speculate on their impact on iron homeostasis and on the immune cells.

The microbiota strongly manipulates the immune system. It is tempting to speculate that the composition and localization of the commensal microbiota in allergic subjects may directly impact the homeostatic iron status of the host, but more studies need to be done.

Conclusions

There is a clear epidemiological connection between a poor iron status and allergy risk, especially in females. Of note, iron-deficient conditions seem to promote a Th2-environment, which is a prerequisite for allergy. Potential contributing factors are endogenous iron levels, allergens capable of binding to iron chelators, and likely a skewed microbiota in allergic subjects.

Conflicts of interest

The authors declare no conflicts of interest.

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References

- 1 United Nations Children's Fund, United Nations University, World Health Organization, Iron Deficiency Anaemia Assessment, Prevention, and Control: A guide for programme managers, WHO/NHD/01.3, 2001, p. 114.
- 2 World Health Organization, Centers for Disease Control and Prevention Technical Consultation. Assessing the iron status of populations, WD 105, 2007, p. 108.
- 3 M. Nairz, I. Theurl, D. Wolf and G. Weiss, Iron deficiency or anemia of inflammation?: Differential diagnosis and

mechanisms of anemia of inflammation, *Wien. Med. Wochenschr.*, 2016, **166**, 411–423.

- 4 G. Papanikolaou and K. Pantopoulos, Systemic iron homeostasis and erythropoiesis, *IUBMB Life*, 2017, **69**, 399–413.
- 5 K. E. Drury, M. Schaeffer and J. I. Silverberg, Association Between Atopic Disease and Anemia in US Children, *JAMA Pediatr.*, 2016, **170**, 29–34.
- 6 T. Haahtela, G. J. Burbach, C. Bachert, C. Bindslev-Jensen, S. Bonini, J. Bousquet, L. Bousquet-Rouanet, P. J. Bousquet, M. Bresciani, A. Bruno, G. W. Canonica, U. Darsow, P. Demoly, S. R. Durham, W. J. Fokkens, S. Giavi, M. Gjomarkaj, C. Gramiccioni, M. L. Kowalski, G. Losonczy, M. Orosz, N. G. Papadopoulos, G. Stingl, A. Todo-Bom, E. von Mutius, A. Kohli, S. Wohrl, S. Jarvenpaa, H. Kautiainen, L. Petman, O. Selroos, T. Zuberbier and L. M. Heinzerling, Clinical relevance is associated with allergen-specific wheal size in skin prick testing, *Clin. Exp. Allergy*, 2014, **44**, 407–416.
- 7 J. R. Chipperfield and C. Ratledge, Salicylic acid is not a bacterial siderophore: a theoretical study, *Biometals*, 2000, **13**, 165–168.
- 8 F. I. Adam, P. L. Bounds, R. Kissner and W. H. Koppenol, Redox properties and activity of iron-citrate complexes: evidence for redox cycling, *Chem. Res. Toxicol.*, 2015, **28**, 604–614.
- 9 R. C. Hider and X. L. Kong, Glutathione: a key component of the cytoplasmic labile iron pool, *Biometals*, 2011, **24**, 1179–1187.
- 10 F. Roth-Walter, P. Starkl, T. Zuberbier, K. Hummel, K. Nobauer, E. Razzazi-Fazeli, R. Brunner, I. Pali-Scholl, J. Kinkel, F. Felix, E. Jensen-Jarolim and T. Kinaciyan, Glutathione exposes sequential IgE-epitopes in ovomucoid relevant in persistent egg allergy, *Mol. Nutr. Food Res.*, 2013, **57**, 536–544.
- 11 A. Meister, Glutathione metabolism and its selective modification, *J. Biol. Chem.*, 1988, **263**, 17205–17208.
- 12 G. A. Kortman, M. Raffatellu, D. W. Swinkels and H. Tjalsma, Nutritional iron turned inside out: intestinal stress from a gut microbial perspective, *FEMS Microbiol. Rev.*, 2014, **38**, 1202–1234.
- 13 G. Pishchany and E. P. Skaar, Taste for blood: hemoglobin as a nutrient source for pathogens, *PLoS Pathog.*, 2012, **8**, e1002535.
- 14 K. Pantopoulos, S. K. Porwal, A. Tartakoff and L. Devireddy, Mechanisms of mammalian iron homeostasis, *Biochemistry*, 2012, **51**, 5705–5724.
- 15 T. Ganz, Macrophages and systemic iron homeostasis, *J. Innate Immun.*, 2012, **4**, 446–453.
- 16 D. D. Funk, Plasma iron turnover in normal subjects, *J. Nucl. Med.*, 1970, **11**, 107–111.
- 17 D. Demeyer, S. De Smet and M. Ulens, The near equivalence of haem and non-haem iron bioavailability and the need for reconsidering dietary iron recommendations, *Eur. J. Clin. Nutr.*, 2014, **68**, 750–751.
- 18 H. Huebers, E. Huebers, W. Forth and W. Rummel, Binding of iron to a non-ferritin protein in the mucosal cells of normal and iron-deficient rats during absorption, *Life Sci.*, 1971, **10**, 1141–1148.



- 19 Y. Nakai, K. Inoue, N. Abe, M. Hatakeyama, K. Y. Ohta, M. Otagiri, Y. Hayashi and H. Yuasa, Functional characterization of human proton-coupled folate transporter/heme carrier protein 1 heterologously expressed in mammalian cells as a folate transporter, *J. Pharmacol. Exp. Ther.*, 2007, **322**, 469–476.
- 20 G. O. Latunde-Dada, K. Takeuchi, R. J. Simpson and A. T. McKie, Haem carrier protein 1 (HCP1): expression and functional studies in cultured cells, *FEBS Lett.*, 2006, **580**, 6865–6870.
- 21 S. Le Blanc, M. D. Garrick and M. Arredondo, Heme carrier protein 1 transports heme and is involved in heme-Fe metabolism, *Am. J. Physiol.: Cell Physiol.*, 2012, **302**, C1780–C1785.
- 22 G. F. da Silva, V. P. Shinkarev, Y. A. Kamensky and G. Palmer, Spectroscopic evidence of the role of an axial ligand histidinate in the mechanism of adrenal cytochrome b561, *Biochemistry*, 2012, **51**, 8730–8742.
- 23 A. T. McKie, D. Barrow, G. O. Latunde-Dada, A. Rolfs, G. Sager, E. Mudaly, M. Mudaly, C. Richardson, D. Barlow, A. Bomford, T. J. Peters, K. B. Raja, S. Shirali, M. A. Hediger, F. Farzaneh and R. J. Simpson, An iron-regulated ferric reductase associated with the absorption of dietary iron, *Science*, 2001, **291**, 1755–1759.
- 24 J. S. Oakhill, S. J. Marritt, E. G. Garetta, R. Cammack and A. T. McKie, Functional characterization of human duodenal cytochrome *b* (Cybrd1): redox properties in relation to iron and ascorbate metabolism, *Biochim. Biophys. Acta*, 2008, **1777**, 260–268.
- 25 S. Ludwiczek, F. I. Rosell, M. L. Ludwiczek and A. G. Mauk, Recombinant expression and initial characterization of the putative human enteric ferric reductase Dcytb, *Biochemistry*, 2008, **47**, 753–761.
- 26 D. J. Lane, D. H. Bae, A. M. Merlot, S. Sahni and D. R. Richardson, Duodenal cytochrome *b* (DCYTB) in iron metabolism: an update on function and regulation, *Nutrients*, 2015, **7**, 2274–2296.
- 27 A. Fini, G. Feroci, G. Fazio and P. Zuman, Interaction of iron(II) with bile salts, *J. Inorg. Biochem.*, 1997, **68**, 251–256.
- 28 A. J. Sanyal, M. L. Shiffmann, J. I. Hirsch and E. W. Moore, Premicellar taurocholate enhances ferrous iron uptake from all regions of rat small intestine, *Gastroenterology*, 1991, **101**, 382–389.
- 29 A. J. Sanyal, J. I. Hirsch and E. W. Moore, Evidence that bile salts are important for iron absorption, *Am. J. Physiol.*, 1994, **266**, G318–G323.
- 30 E. C. Theil, H. Chen, C. Miranda, H. Janser, B. Elsenhans, M. T. Nunez, F. Pizarro and K. Schumann, Absorption of iron from ferritin is independent of heme iron and ferrous salts in women and rat intestinal segments, *J. Nutr.*, 2012, **142**, 478–483.
- 31 J. M. Christensen, M. Ghannam and J. W. Ayres, Effects of divalent amino acids on iron absorption, *J. Pharm. Sci.*, 1984, **73**, 1245–1248.
- 32 A. Donovan, A. Brownlie, Y. Zhou, J. Shepard, S. J. Pratt, J. Moynihan, B. H. Paw, A. Drejer, B. Barut, A. Zapata, T. C. Law, C. Brugnara, S. E. Lux, G. S. Pinkus, J. L. Pinkus, P. D. Kingsley, J. Palis, M. D. Fleming, N. C. Andrews and L. I. Zon, Positional cloning of zebrafish ferroportin1 identifies a conserved vertebrate iron exporter, *Nature*, 2000, **403**, 776–781.
- 33 S. Clemens, Zn and Fe biofortification: the right chemical environment for human bioavailability, *Plant Sci.*, 2014, **225**, 52–57.
- 34 M. Dell'mour, W. Schenkeveld, E. Oburger, L. Fischer, S. Kraemer, M. Puschenreiter, M. Lammerhofer, G. Koellensperger and S. Hann, Analysis of iron-phytosiderophore complexes in soil related samples: LC-ESI-MS/MS versus CE-MS, *Electrophoresis*, 2012, **33**, 726–733.
- 35 J. R. Hunt and Z. K. Roughead, Nonheme-iron absorption, fecal ferritin excretion, and blood indexes of iron status in women consuming controlled lactoovo vegetarian diets for 8 wk, *Am. J. Clin. Nutr.*, 1999, **69**, 944–952.
- 36 J. Suliburska, P. Bogdanski, M. Szulinska, M. Stepien, D. Pupek-Musialik and A. Jablecka, Effects of green tea supplementation on elements, total antioxidants, lipids, and glucose values in the serum of obese patients, *Biol. Trace Elem. Res.*, 2012, **149**, 315–322.
- 37 N. R. Perron and J. L. Brumaghim, A review of the antioxidant mechanisms of polyphenol compounds related to iron binding, *Cell Biochem. Biophys.*, 2009, **53**, 75–100.
- 38 A. Imessaoudene, H. Merzouk, F. Berroukeche, N. Mokhtari, B. Bensenane, S. Cherrak, S. A. Merzouk and M. Elhabiri, Beneficial effects of quercetin-iron complexes on serum and tissue lipids and redox status in obese rats, *J. Nutr. Biochem.*, 2016, **29**, 107–115.
- 39 P. Schwarz, J. A. Kubler, P. Strnad, K. Muller, T. F. Barth, A. Gerloff, P. Feick, C. Peyssonnaud, S. Vaultont, G. Adler and H. Kulaksiz, Hepsidin is localised in gastric parietal cells, regulates acid secretion and is induced by Helicobacter pylori infection, *Gut*, 2012, **61**, 193–201.
- 40 T. E. Galesloot, S. H. Vermeulen, A. J. Geurts-Moespot, S. M. Klaver, J. J. Kroot, D. van Tienoven, J. F. Wetzels, L. A. Kiemeneij, F. C. Sweep, M. den Heijer and D. W. Swinkels, Serum hepsidin: reference ranges and biochemical correlates in the general population, *Blood*, 2011, **117**, e218–e225.
- 41 G. Ramey, J. C. Deschemin, B. Durel, F. Canonne-Hergaux, G. Nicolas and S. Vaultont, Hepsidin targets ferroportin for degradation in hepatocytes, *Haematologica*, 2010, **95**, 501–504.
- 42 T. Nakanishi, Y. Hasuike, M. Nanami, M. Yahiro and T. Kuragano, Novel iron-containing phosphate binders and anemia treatment in CKD: oral iron intake revisited, *Nephrol., Dial., Transplant.*, 2016, **31**, 1588–1594.
- 43 M. Munoz, J. A. Garcia-Erce and A. F. Remacha, Disorders of iron metabolism. Part 1: molecular basis of iron homeostasis, *J. Clin. Pathol.*, 2011, **64**, 281–286.
- 44 A. Rolfs, I. Kvietikova, M. Gassmann and R. H. Wenger, Oxygen-regulated transferrin expression is mediated by hypoxia-inducible factor-1, *J. Biol. Chem.*, 1997, **272**, 20055–20062.



- 45 A. M. Silva and R. C. Hider, Influence of non-enzymatic post-translation modifications on the ability of human serum albumin to bind iron. Implications for non-transferrin-bound iron speciation, *Biochim. Biophys. Acta*, 2009, **1794**, 1449–1458.
- 46 Y. Ma, H. de Groot, Z. Liu, R. C. Hider and F. Petrat, Chelation and determination of labile iron in primary hepatocytes by pyridinone fluorescent probes, *Biochem. J.*, 2006, **395**, 49–55.
- 47 L. de Swart, J. C. Hendriks, L. N. van der Vorm, Z. I. Cabantchik, P. J. Evans, E. A. Hod, G. M. Brittenham, Y. Furman, B. Wojczyk, M. C. Janssen, J. B. Porter, V. E. Mattijssen, B. J. Biemond, M. A. MacKenzie, R. Origa, R. Galanello, R. C. Hider and D. W. Swinkels, Second international round robin for the quantification of serum non-transferrin-bound iron and labile plasma iron in patients with iron-overload disorders, *Haematologica*, 2016, **101**, 38–45.
- 48 J. L. Beard, Iron biology in immune function, muscle metabolism and neuronal functioning, *J. Nutr.*, 2001, **131**, 568S–579S, discussion 580S.
- 49 E. S. Wintergerst, S. Maggini and D. H. Hornig, Contribution of selected vitamins and trace elements to immune function, *Ann. Nutr. Metab.*, 2007, **51**, 301–323.
- 50 D. Z. de Back, E. B. Kostova, M. van Kraaij, T. K. van den Berg and R. van Bruggen, Of macrophages and red blood cells; a complex love story, *Front. Physiol.*, 2014, **5**, 9.
- 51 S. Recalcati, M. Locati, A. Marini, P. Santambrogio, F. Zaninotto, M. De Pizzol, L. Zammataro, D. Girelli and G. Cairo, Differential regulation of iron homeostasis during human macrophage polarized activation, *Eur. J. Immunol.*, 2010, **40**, 824–835.
- 52 J. P. Pinto, J. Arezes, V. Dias, S. Oliveira, I. Vieira, M. Costa, M. Vos, A. Carlsson, Y. Rikers, M. Rangel and G. Porto, Physiological implications of NTBI uptake by T lymphocytes, *Front. Pharmacol.*, 2014, **5**, 24.
- 53 H. H. Jabara, S. E. Boyden, J. Chou, N. Ramesh, M. J. Massaad, H. Benson, W. Bainter, D. Fraulino, F. Rahimov, C. Sieff, Z. J. Liu, S. H. Alshemmari, B. K. Al-Ramadi, H. Al-Dhekri, R. Arnaout, M. Abu-Shukair, A. Vatsayan, E. Silver, S. Ahuja, E. G. Davies, M. Sola-Visner, T. K. Ohsumi, N. C. Andrews, L. D. Notarangelo, M. D. Fleming, W. Al-Herz, L. M. Kunkel and R. S. Geha, A missense mutation in TFRC, encoding transferrin receptor 1, causes combined immunodeficiency, *Nat. Genet.*, 2016, **48**, 74–78.
- 54 K. C. Bergmann, J. Heinrich and H. Niemann, Current status of allergy prevalence in Germany: position paper of the Environmental Medicine Commission of the Robert Koch Institute, *Allergol. J. Int.*, 2016, **25**, 6–10.
- 55 K. D. Jackson, L. D. Howie and L. J. Akinbami, Trends in allergic conditions among children: United States, 1997–2011, *NCHS Data Brief*, 2013, 1–8.
- 56 I. Pali-Scholl, J. Namazy and E. Jensen-Jarolim, Allergic diseases and asthma in pregnancy, a secondary publication, *World Allergy Organ. J.*, 2017, **10**, 10.
- 57 R. Weigert, N. C. Dosch, M. E. Bacsik-Campbell, T. W. Guilbert, C. L. Coe and P. J. Kling, Maternal pregnancy weight gain and cord blood iron status are associated with eosinophilia in infancy, *J. Perinatol.*, 2015, **35**, 621–626.
- 58 M. K. Georgieff, R. L. Schmidt, M. M. Mills, W. J. Radmer and J. A. Widness, Fetal iron and cytochrome *c* status after intrauterine hypoxemia and erythropoietin administration, *Am. J. Physiol.*, 1992, **262**, R485–R491.
- 59 B. I. Nwaru, H. Hayes, L. Gambling, L. C. Craig, K. Allan, N. Prabhu, S. W. Turner, G. McNeill, M. Erkkola, A. Seaton, H. J. McArdle and G. Devereux, An exploratory study of the associations between maternal iron status in pregnancy and childhood wheeze and atopy, *Br. J. Nutr.*, 2014, **112**, 2018–2027.
- 60 S. O. Shaheen, R. B. Newson, A. J. Henderson, P. M. Emmett, A. Sherriff, M. Cooke and A. S. Team, Umbilical cord trace elements and minerals and risk of early childhood wheezing and eczema, *Eur. Respir. J.*, 2004, **24**, 292–297.
- 61 T. J. David, F. E. Wells, T. C. Sharpe, A. C. Gibbs and J. Devlin, Serum levels of trace metals in children with atopic eczema, *Br. J. Dermatol.*, 1990, **122**, 485–489.
- 62 S. Y. Oh, J. Chung, M. K. Kim, S. O. Kwon and B. H. Cho, Antioxidant nutrient intakes and corresponding biomarkers associated with the risk of atopic dermatitis in young children, *Eur. J. Clin. Nutr.*, 2010, **64**, 245–252.
- 63 C. T. McEvoy, D. Schilling, N. Clay, K. Jackson, M. D. Go, P. Spitale, C. Bunten, M. Leiva, D. Gonzales, J. Hollister-Smith, M. Durand, B. Frei, A. S. Buist, D. Peters, C. D. Morris and E. R. Spindel, Vitamin C supplementation for pregnant smoking women and pulmonary function in their newborn infants: a randomized clinical trial, *JAMA*, 2014, **311**, 2074–2082.
- 64 H. Maazi, S. Shirinbak, N. Bloksma, M. C. Nawijn and A. J. van Oosterhout, Iron administration reduces airway hyperreactivity and eosinophilia in a mouse model of allergic asthma, *Clin. Exp. Immunol.*, 2011, **166**, 80–86.
- 65 M. Gharagozloo, M. Karimi and Z. Amirghofran, Double-faced cell-mediated immunity in beta-thalassemia major: stimulated phenotype versus suppressed activity, *Ann. Hematol.*, 2009, **88**, 21–27.
- 66 G. Pardalos, F. Kanakoudi-Tsakalidis, M. Malaka-Zafiriou, H. Tsantali, M. Athanasiou-Metaxa, G. Kallinikos and G. Papaevangelou, Iron-related disturbances of cell-mediated immunity in multitransfused children with thalassemia major, *Clin. Exp. Immunol.*, 1987, **68**, 138–145.
- 67 E. Jensen-Jarolim and E. Untersmayr, Gender-medicine aspects in allergology, *Allergy*, 2008, **63**, 610–615.
- 68 U. Langen, R. Schmitz and H. Steppuhn, Prevalence of allergic diseases in Germany: results of the German Health Interview and Examination Survey for Adults (DEGS1), *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz*, 2013, **56**, 698–706.
- 69 C. Fonseca, F. Marques, A. Robalo Nunes, A. Belo, D. Brillhante and J. Cortez, Prevalence of anaemia and iron deficiency in Portugal: the EMPIRE study, *Intern. Med. J.*, 2016, **46**, 470–478.
- 70 G. Alvarez-Uria, P. K. Naik, M. Midde, P. S. Yalla and R. Pakam, Prevalence and severity of anaemia stratified



- by age and gender in rural India, *Anemia*, 2014, **2014**, 176182.
- 71 E. Jensen-Jarolim, M. C. Turner and S. N. Karagiannis, AllergoOncology: IgE- and IgG4-mediated immune mechanisms linking allergy with cancer and their translational implications, *J. Allergy Clin. Immunol.*, 2017, **140**, 982–984.
- 72 E. Jensen-Jarolim, G. Achatz, M. C. Turner, S. Karagiannis, F. Legrand, M. Capron, M. L. Penichet, J. A. Rodriguez, A. G. Siccardi, L. Vangelista, A. B. Riemer and H. Gould, AllergoOncology: the role of IgE-mediated allergy in cancer, *Allergy*, 2008, **63**, 1255–1266.
- 73 A. C. Chua, M. W. Knuiman, D. Trinder, M. L. Divitini and J. K. Olynyk, Higher concentrations of serum iron and transferrin saturation but not serum ferritin are associated with cancer outcomes, *Am. J. Clin. Nutr.*, 2016, **104**, 736–742.
- 74 H. Cao, C. Wang, R. Chai, Q. Dong and S. Tu, Iron intake, serum iron indices and risk of colorectal adenomas: a meta-analysis of observational studies, *Eur. J. Cancer Care*, 2017, **26**, e12486.
- 75 C. P. Wen, J. H. Lee, Y. P. Tai, C. Wen, S. B. Wu, M. K. Tsai, D. P. Hsieh, H. C. Chiang, C. A. Hsiung, C. Y. Hsu and X. Wu, High serum iron is associated with increased cancer risk, *Cancer Res.*, 2014, **74**, 6589–6597.
- 76 A. G. Mainous, 3rd, J. M. Gill and C. J. Everett, Transferrin saturation, dietary iron intake, and risk of cancer, *Ann. Fam. Med.*, 2005, **3**, 131–137.
- 77 A. G. Mainous, 3rd, B. J. Wells, R. J. Koopman, C. J. Everett and J. M. Gill, Iron, lipids, and risk of cancer in the Framingham Offspring cohort, *Am. J. Epidemiol.*, 2005, **161**, 1115–1122.
- 78 B. J. Wells, A. G. Mainous, 3rd, C. J. Everett and J. M. Gill, Iron, cholesterol, and the risk of cancer in an 18-year cohort, *Asian Pac. J. Cancer Prev.*, 2005, **6**, 505–509.
- 79 A. Sica and A. Mantovani, Macrophage plasticity and polarization: *in vivo* veritas, *J. Clin. Invest.*, 2012, **122**, 787–795.
- 80 J. A. Thorson, K. M. Smith, F. Gomez, P. W. Naumann and J. D. Kemp, Role of iron in T cell activation: TH1 clones differ from TH2 clones in their sensitivity to inhibition of DNA synthesis caused by IgG Mabs against the transferrin receptor and the iron chelator deferoxamine, *Cell. Immunol.*, 1991, **134**, 126–137.
- 81 S. Leung, A. Holbrook, B. King, H. T. Lu, V. Evans, N. Miyamoto, C. Mallari, S. Harvey, D. Davey, E. Ho, W. W. Li, J. Parkinson, R. Horuk, S. Jaroch, M. Berger, W. Skuballa, C. West, R. Pulk, G. Phillips, J. Bryant, B. Subramanyam, C. Schaefer, H. Salamon, E. Lyons, D. Schilling, H. Seidel, J. Kraetzschmar, M. Snider and D. Perez, Differential inhibition of inducible T cell cytokine secretion by potent iron chelators, *J. Biomol. Screening*, 2005, **10**, 157–167.
- 82 G. Corna, L. Campana, E. Pignatti, A. Castiglioni, E. Tagliafico, L. Bosurgi, A. Campanella, S. Brunelli, A. A. Manfredi, P. Apostoli, L. Silvestri, C. Camaschella and P. Rovere-Querini, Polarization dictates iron handling by inflammatory and alternatively activated macrophages, *Haematologica*, 2010, **95**, 1814–1822.
- 83 J. W. Larrick and P. Cresswell, Transferrin receptors on human B and T lymphoblastoid cell lines, *Biochim. Biophys. Acta*, 1979, **583**, 483–490.
- 84 P. A. Seligman, J. Kovar, R. B. Schleicher and E. W. Gelfand, Transferrin-independent iron uptake supports B lymphocyte growth, *Blood*, 1991, **78**, 1526–1531.
- 85 G. Li, E. J. Pone, D. C. Tran, P. J. Patel, L. Dao, Z. Xu and P. Casali, Iron inhibits activation-induced cytidine deaminase enzymatic activity and modulates immunoglobulin class switch DNA recombination, *J. Biol. Chem.*, 2012, **287**, 21520–21529.
- 86 Y. S. Jang, G. Y. Seo, J. M. Lee, H. Y. Seo, H. J. Han, S. J. Kim, B. R. Jin, H. J. Kim, S. R. Park, K. J. Rhee, W. S. Kim and P. H. Kim, Lactoferrin causes IgA and IgG2b isotype switching through betaglycan binding and activation of canonical TGF-beta signaling, *Mucosal Immunol.*, 2015, **8**, 906–917.
- 87 K. Nakashima, T. Takeuchi and T. Shirakawa, Differentiation, distribution, and chemical state of intracellular trace elements in LAD2 mast cell line, *Biol. Trace Elem. Res.*, 2005, **108**, 105–114.
- 88 M. Shalit, A. Tedeschi, A. Miadonna and F. Levi-Schaffer, Desferal (desferrioxamine)—a novel activator of connective tissue-type mast cells, *J. Allergy Clin. Immunol.*, 1991, **88**, 854–860.
- 89 S. Higa, T. Hirano, M. Kotani, M. Matsumoto, A. Fujita, M. Suemura, I. Kawase and T. Tanaka, Fisetin, a flavonol, inhibits TH2-type cytokine production by activated human basophils, *J. Allergy Clin. Immunol.*, 2003, **111**, 1299–1306.
- 90 A. Singh, A. Demont, L. Actis-Goretta, S. Holvoet, A. Leveques, M. Lepage, S. Nutten and A. Mercenier, Identification of epicatechin as one of the key bioactive constituents of polyphenol-enriched extracts that demonstrate an anti-allergic effect in a murine model of food allergy, *Br. J. Nutr.*, 2014, **112**, 358–368.
- 91 D. F. Finn and J. J. Walsh, Twenty-first century mast cell stabilizers, *Br. J. Pharmacol.*, 2013, **170**, 23–37.
- 92 S. K. Kritas, A. Saggini, G. Varvara, G. Murmura, A. Caraffa, P. Antinolfi, E. Toniato, A. Pantalone, G. Neri, S. Frydas, M. Rosati, M. Tei, A. Speziali, R. Saggini, F. Pandolfi, G. Cerulli, T. C. Theoharides and P. Conti, Luteolin inhibits mast cell-mediated allergic inflammation, *J. Biol. Regul. Homeostatic Agents*, 2013, **27**, 955–959.
- 93 Y. Shi, J. Dai, H. Liu, R. R. Li, P. L. Sun, Q. Du, L. L. Pang, Z. Chen and K. S. Yin, Naringenin inhibits allergen-induced airway inflammation and airway responsiveness and inhibits NF-kappaB activity in a murine model of asthma, *Can. J. Physiol. Pharmacol.*, 2009, **87**, 729–735.
- 94 M. J. Bae, H. S. Shin, H. J. See, S. Y. Jung, D. A. Kwon and D. H. Shon, Baicalein induces CD4(+)Foxp3(+) T cells and enhances intestinal barrier function in a mouse model of food allergy, *Sci. Rep.*, 2016, **6**, 32225.
- 95 H. Kang, C. H. Lee, J. R. Kim, J. Y. Kwon, M. J. Son, J. E. Kim and K. W. Lee, Theobroma cacao extract



- of green tea polyphenol, epigallocatechin-3-gallate, and 2S albumins of peanut, *Food Chem.*, 2015, **185**, 309–317.
- 125 E. L. van Boxtel, L. A. van den Broek, S. J. Koppelman, J. P. Vincken and H. Gruppen, Peanut allergen Ara h 1 interacts with proanthocyanidins into higher molecular weight complexes, *J. Agric. Food Chem.*, 2007, **55**, 8772–8778.
- 126 A. Casanal, U. Zander, F. Dupeux, V. Valpuesta and J. A. Marquez, Purification, crystallization and preliminary X-ray analysis of the strawberry allergens Fra a 1E and Fra a 3 in the presence of catechin, *Acta Crystallogr., Sect. F: Struct. Biol. Cryst. Commun.*, 2013, **69**, 510–514.
- 127 G. M. Escandar and L. F. Sala, Complexing behavior of rutin and quercetin, *Can. J. Chem.*, 1991, **69**, 1994–2001.
- 128 E. Jensen-Jarolim, L. F. Pacios, R. Bianchini, G. Hofstetter and F. Roth-Walter, Structural similarities of human and mammalian lipocalins, and their function in innate immunity and allergy, *Allergy*, 2016, **71**, 286–294.
- 129 D. P. Strachan, Hay fever, hygiene, and household size, *BMJ*, 1989, **299**, 1259–1260.
- 130 E. von Mutius and D. Vercelli, Farm living: effects on childhood asthma and allergy, *Nat. Rev. Immunol.*, 2010, **10**, 861–868.
- 131 M. Rajilic-Stojanovic and W. M. de Vos, The first 1000 cultured species of the human gastrointestinal microbiota, *FEMS Microbiol. Rev.*, 2014, **38**, 996–1047.
- 132 J. Qin, R. Li, J. Raes, M. Arumugam, K. S. Burgdorf, C. Manichanh, T. Nielsen, N. Pons, F. Levenez, T. Yamada, D. R. Mende, J. Li, J. Xu, S. Li, D. Li, J. Cao, B. Wang, H. Liang, H. Zheng, Y. Xie, J. Tap, P. Lepage, M. Bertalan, J. M. Batto, T. Hansen, D. Le Paslier, A. Linneberg, H. B. Nielsen, E. Pelletier, P. Renault, T. Sicheritz-Ponten, K. Turner, H. Zhu, C. Yu, S. Li, M. Jian, Y. Zhou, Y. Li, X. Zhang, S. Li, N. Qin, H. Yang, J. Wang, S. Brunak, J. Dore, F. Guarner, K. Kristiansen, O. Pedersen, J. Parkhill, J. Weissenbach, H. I. T. C. Meta, P. Bork, S. D. Ehrlich and J. Wang, A human gut microbial gene catalogue established by metagenomic sequencing, *Nature*, 2010, **464**, 59–65.
- 133 R. Balfour Sartor, Bacteria in Crohn's disease: mechanisms of inflammation and therapeutic implications, *J. Clin. Gastroenterol.*, 2007, **41**(suppl 1), S37–S43.
- 134 K. S. Josefsson, M. T. Baldridge, C. S. Kadmon and K. Y. King, Antibiotics impair murine hematopoiesis by depleting the intestinal microbiota, *Blood*, 2017, **129**, 729–739.
- 135 A. Dostal, C. Lacroix, V. T. Pham, M. B. Zimmermann, C. Del'homme, A. Bernalier-Donadille and C. Chassard, Iron supplementation promotes gut microbiota metabolic activity but not colitis markers in human gut microbiota-associated rats, *Br. J. Nutr.*, 2014, **111**, 2135–2145.
- 136 M. Kalliomaki, P. Kirjavainen, E. Eerola, P. Kero, S. Salminen and E. Isolauri, Distinct patterns of neonatal gut microflora in infants in whom atopy was and was not developing, *J. Allergy Clin. Immunol.*, 2001, **107**, 129–134.
- 137 Z. Ling, Z. Li, X. Liu, Y. Cheng, Y. Luo, X. Tong, L. Yuan, Y. Wang, J. Sun, L. Li and C. Xiang, Altered fecal microbiota composition associated with food allergy in infants, *Appl. Environ. Microbiol.*, 2014, **80**, 2546–2554.
- 138 R. Berni Canani, N. Sangwan, A. T. Stefka, R. Nocerino, L. Paparo, R. Aitoro, A. Calignano, A. A. Khan, J. A. Gilbert and C. R. Nagler, Lactobacillus rhamnosus GG-supplemented formula expands butyrate-producing bacterial strains in food allergic infants, *ISME J.*, 2016, **10**, 742–750.
- 139 M. Candela, S. Rampelli, S. Turrone, M. Severgnini, C. Consolandi, G. De Bellis, R. Masetti, G. Ricci, A. Pession and P. Brigidi, Unbalance of intestinal microbiota in atopic children, *BMC Microbiol.*, 2012, **12**, 95.
- 140 C. C. Chen, K. J. Chen, M. S. Kong, H. J. Chang and J. L. Huang, Alterations in the gut microbiotas of children with food sensitization in early life, *Pediatr. Allergy Immunol.*, 2016, **27**, 254–262.
- 141 K. E. Fujimura, A. R. Sitarik, S. Havstad, D. L. Lin, S. Levan, D. Fadrosch, A. R. Panzer, B. LaMere, E. Rackaityte, N. W. Lukacs, G. Wegienka, H. A. Boushey, D. R. Ownby, E. M. Zoratti, A. M. Levin, C. C. Johnson and S. V. Lynch, Neonatal gut microbiota associates with childhood multi-sensitized atopy and T cell differentiation, *Nat. Med.*, 2016, **22**, 1187–1191.
- 142 M. Rajilic-Stojanovic, H. G. Heilig, S. Tims, E. G. Zoetendal and W. M. de Vos, Long-term monitoring of the human intestinal microbiota composition, *Environ. Microbiol.*, 2013, **15**, 1146–1159.
- 143 X. Hua, J. J. Goedert, A. Pu, G. Yu and J. Shi, Allergy associations with the adult fecal microbiota: analysis of the American Gut Project, *EBioMedicine*, 2016, **3**, 172–179.
- 144 N. Fyhrquist, L. Ruokolainen, A. Suomalainen, S. Lehtimäki, V. Veckman, J. Vendelin, P. Karisola, M. Lehto, T. Savinko, H. Jarva, T. U. Kosunen, J. Corander, P. Auvinen, L. Paulin, L. von Hertzen, T. Laatikainen, M. Makela, T. Haahtela, D. Greco, I. Hanski and H. Alenius, Acinetobacter species in the skin microbiota protect against allergic sensitization and inflammation, *J. Allergy Clin. Immunol.*, 2014, **134**, 1301–1309 e1311.
- 145 E. A. Kennedy, J. Connolly, J. O. Hourihane, P. G. Fallon, W. H. McLean, D. Murray, J. H. Jo, J. A. Segre, H. H. Kong and A. D. Irvine, Skin microbiome before development of atopic dermatitis: Early colonization with commensal staphylococci at 2 months is associated with a lower risk of atopic dermatitis at 1 year, *J. Allergy Clin. Immunol.*, 2017, **139**, 166–172.
- 146 J. Jalanka-Tuovinen, A. Salonen, J. Nikkila, O. Immonen, R. Kekkonen, L. Lahti, A. Palva and W. M. de Vos, Intestinal microbiota in healthy adults: temporal analysis reveals individual and common core and relation to intestinal symptoms, *PLoS One*, 2011, **6**, e23035.
- 147 J. Jalanka-Tuovinen, J. Salojarvi, A. Salonen, O. Immonen, K. Garsed, F. M. Kelly, A. Zaitoun, A. Palva, R. C. Spiller and W. M. de Vos, Faecal microbiota composition and



- host-microbe cross-talk following gastroenteritis and in postinfectious irritable bowel syndrome, *Gut*, 2014, **63**, 1737–1745.
- 148 J. A. Shapiro and T. A. Wencewicz, Acinetobactin Isomerization Enables Adaptive Iron Acquisition in *Acinetobacter baumannii* through pH-Triggered Siderophore Swapping, *ACS Infect. Dis.*, 2016, **2**, 157–168.
- 149 B. H. Baig, I. K. Wachsmuth and G. K. Morris, Utilization of exogenous siderophores by *Campylobacter* species, *J. Clin. Microbiol.*, 1986, **23**, 431–433.
- 150 D. Jovanovic, N. Ilic, B. Miljkovic-Selimovic, D. Djokic, T. Relic, Z. Tambur, R. Doder and G. Kostic, *Campylobacter jejuni* infection and IgE sensitization in up to 2-year-old infants, *Vojnosanit. Pregl.*, 2015, **72**, 140–147.

