

REVIEW ARTICLE

Structural similarities of human and mammalian lipocalins, and their function in innate immunity and allergy

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Abstract

Owners and their domestic animals via skin shedding and secretions, mutually exchange microbiomes, potential pathogens and innate immune molecules. Among the latter especially lipocalins are multifaceted: they may have an immunomodulatory function and, furthermore, they represent one of the most important animal allergen families. The amino acid identities, as well as their structures by superposition modeling were compared among human lipocalins, hLCN1 and hLCN2, and most important animal lipocalin allergens, such as Can f 1, Can f 2 and Can f 4 from dog, Fel d 4 from cats, Bos d 5 from cow's milk, Equ c 1 from horses, and Mus m 1 from mice, all of them representing major allergens. The β -barrel fold with a central molecular pocket is similar among human and animal lipocalins. Thereby, lipocalins are able to transport a variety of biological ligands in their highly conserved calyx-like cavity, among them siderophores with the strongest known capability to complex iron (Fe^{3+}). Levels of human lipocalins are elevated in nonallergic inflammation and cancer, associated with innate immunoregulatory functions that critically depend on ligand load. Accordingly, deficient loading of lipocalin allergens establishes their capacity to induce Th2 hypersensitivity. Our similarity analysis of human and mammalian lipocalins highlights their function in innate immunity and allergy.

The current view on immune tolerance vs Th2 skewing of allergens

IgE-mediated allergy is characterized by a Th2-dominant immune response. The formed IgE may be directed against the genuine allergen or secondarily bind to molecules with similar epitopes on their surface, causing the phenomenon of cross-reactivity. A limited number of allergen families can initiate Th2 responses strong enough to result in IgE formation in spite of sometimes having limited amino acid homologies. In these settings, functional similarity may be a dominant feature for their Th2 induction capacity.

Consequently, it is essential to understand the very first events that actually skew the immune response to Th2. Immune cells like NKT, eosinophils (that especially in the small intestine via CD103 DC activation control Th2 priming

(1)), basophils (2), nuocytes, and NKT cells (3), but also macrophages (4) are known sources of early IL-4 and IL-13. These cytokines are released quickly upon stimulating the cells under involvement of a Notch-regulated CNS-2 enhancer (5) and the events are connected to memory in CD4 T cells (2). Disturbances of the skin and mucosal barriers and subsequent TSLP release may be crucial upstream events (6). One explanation could be that some allergens have enzymatic functions and thereby produce an epithelial danger signal (7), but many allergens have no proteolytic activity and do still exert 'adjuvant-like activation' (8). It is thus not entirely clear which danger signals go along with allergens that initiate priming or triggering of these cells to release Th2 cytokines, and would thereby mark allergens as *special*. It is noteworthy that among the known protein families in the 2009 Pfam database only 1.4% are considered allergens (9). In the case

of respiratory mammalian allergens a few protein families are absolutely dominant: lipocalins, secretoglobins and kallikreins (10), and IgE levels against them correlate with the severity of asthma (11).

Animal keeping: who is at risk?

The question of whether interactions with animals provide protection or increase risk is hotly debated, with particular points of discussion being the subject's age at time of exposure, and the exact animal species or breed. In German-speaking Europe between 16% and 25% of households own cats, and 12% dogs (Table 1), with an estimated dark number of plus 30%. The interrelation between people and domestic animals has thus considerably changed in the last decades. Humans and pets in Western societies are cohabitating more close and in a cleaner way than ever before, a development which is associated with a good economy. Simultaneously, the rates of allergies and asthma in human patients caused by animal dander are increasing (12). In a cohort study of 696 school children 259 were sensitized to animals, and the majority of them to multiple species (13). The higher awareness today of allergy risk associated with pet ownership and the desire for nonfurry pet animals go hand in hand, introducing novel, alternative allergen threats into homes such as those presented from feed insects for reptiles (14). However, pets may also shuttle traditional allergens into homes: house dust mites can be identified in bedding, skin and hair coats of dogs (15). Interestingly, also pet animals and horses increasingly suffer from atopic eczema and other forms of allergies (16, 17). Therefore, it might be important to look at the problem bi-directionally and watch for systematic problems in our society and environment.

In contrast to the earlier trend to minimize allergen release by washing pets (18), most recent work suggests that the introduction of pets into homes early in life is protective (19). It has further been shown that lowering pet exposure may reduce the IgE and symptom levels if allergy is established (20). The interplay of allergens and the microbiome may be decisive for inducing hypersensitivity: Low levels of Firmicutes and Bacteroidetes in the skin flora concomitant with high allergen exposure enhance the risk for atopy and

asthma (21). Needless to say that forced hygiene, washing and disturbance of the skin pH, enzymatic shampooing (7), and even the water quality (22), may impact the physiologic skin flora (23). In some studies cat and dog ownership did not elevate the risk of asthma (24), which might be correlated with exposure to the associated 'good' microbiomes of the animals. However, people with dog allergy more seldom keep dogs (25).

The observation that there are breed-specific differences in eliciting symptoms has initiated the search for 'hypoallergenic' cats, dogs, and horses and stimulates breeders to single out mutants. The experimental evidence, however, is sparse and this topic needs to be addressed in its whole complexity regarding the countless breeds of domestic animals. The situation gets even more complicated as an animal's age and gender also play a role in allergies to them (26). Here, molecular diagnosis has significantly contributed to important practical recommendations (19), including the neutering, or avoidance of male animals (27, 28). Whereas the expectations were that hypoallergenic animals would shed less allergens, the contrary turned out to be the case: in a recent study putative hypoallergenic dogs produced higher levels of Can f 1, a lipocalin allergen (29).

Comparing animal, human, and other lipocalins

What is not yet understood is why allergens in particular provoke a Th2 shift in the immune response and lead to IgE production. Why exactly, are lipocalins so important elicitors of allergies to animals even though humans also do express lipocalins, a fact that is maybe less known to the allergist?

Lipocalins owe their name to the fact that they usually carry lipids (or other hydrophobic compounds) accommodated in a large, calyx-like cavity formed by their characteristic β -barrel fold (Fig. 1). Ligand specificity of lipocalins is regulated by the amino acid residues that line their binding pocket. A large variety of ligands, most of them hydrophobic or amphiphilic, binds to lipocalins that include lipids, steroids, hormones as well as metabolites such as vitamins, cofactors, and odorants. In some cases, binding of the ligand is critical for the biological functions of the lipocalin.

Exploring the PDB by entering the query 'lipocalin', renders nearly 300 experimental structures available for lipocalins belonging to 24 eukaryotic species and 10 bacteria species of which 79 structures correspond to humans (Table 2).

However, these numbers include mutants, engineered variants and the same protein in complex with different ligands, particularly for the most studied cases such as bovine, murine, and human lipocalins.

Allergenic lipocalins have been especially identified in furry animals (19), for instance in dogs: Can f 1, -2, -4, -6, cats: Fel d 4, -7, mice: Mus m 1, horses: Equ c 1, guinea pigs: Cav p 2, -3 (30), and hamsters (31). Lipocalins are also found in tick saliva (32) where they sequester histamine and thereby interfere with its signaling via H1 receptor (32), and contribute to camouflaging the bite. Importantly, humans also express 'a menagerie of lipocalins' (33), such as LCN2 (alternatively called siderocalin/SCN; neutrophil gelatinase-associated

Table 1 Statistical comparison of percentage and numbers of animals in German-speaking households (Statistics Germany <http://www.wissenswertes.at/index.php?id=haustiere-statistik>)

Species	Austria (%)	Switzerland (%)	Germany (%)	Numbers in Germany (Mio.)
Cats	25.6	25	16.5	8.2
Dogs	30	12	13.3	5.4
Rodents		11	6.4	5.6
Birds		7	4.9	3.4
Aquaria		6	4.4	2.0
Ponds			4.0	2.1
Terraria			1.2	0.4

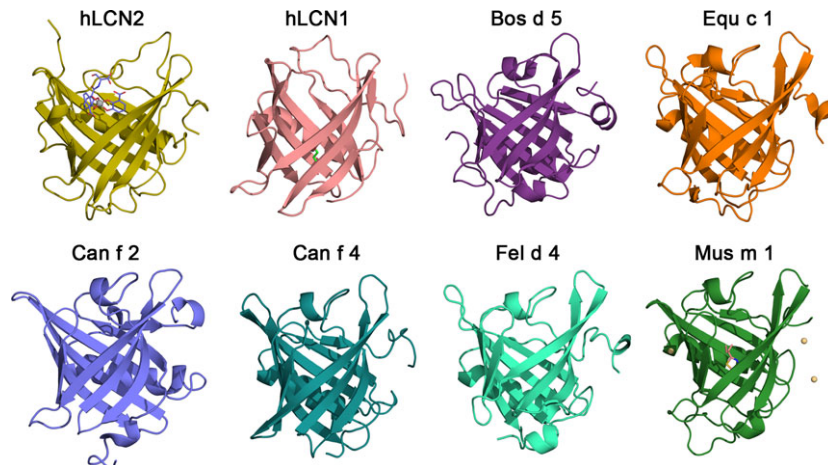


Figure 1 Gallery of human and animal lipocalins. PDB codes for experimental structures are given in parentheses. hLCN2: human LCN2 in complex with the siderophore enterobactin shown as sticks chelating the central Fe^{3+} ion shown as a gray sphere (1L6M (82)). hLCN1: human tear lipocalin in complex with 1,4-butanediol (3EYC (83)). Bos d 5: bovine β -lactoglobulin unliganded form (3NPO (84)).

Equ c 1: major horse allergen (1EW3 (85)). Can f 2: dog allergen (3L4R (45)) with IgE cross-reactivity with the cat allergen Fel d 4. Can f 4: dog dander allergen (4ODD (86)). Fel d 4: cat allergen, homology model structure based on template Equ c 1. Mus m 1: pheromone binding rodent major urinary protein in complex with 2-(sec-butyl)-thiazole and Cd^{2+} ions shown as yellow spheres (1MUP (87)).

lipocalin/NGAL, 24p3), or human LCN1 (alias tear lipocalin, TLC). A gallery of human and animal lipocalins for which experimental structures exist is represented in Fig. 1. Their well-recognized characteristic β -barrel fold has emerged in the last few years as a successful molecular scaffold to engineer novel binding proteins, so called anticalins, with human lipocalins playing a particularly relevant role in clinical applications (33). In an innovative approach four different canine lipocalins were recently linked into one multimeric molecule which indeed induced IgG upon vaccinating mice and which therefore may be used for vaccination against dog allergy in the future (34).

Lipocalins occur in secretions such as saliva, in urine (besides kallikreins) (28), and shed skin, which are all important sources for the release of allergens into our environment (35). Taken the intense interactions between owner and animal it is plausible that there is a bidirectional exchange of allergens, as it is the case with phylotypes of the microbiome of human dog owners and dogs (36).

Given their importance, many lipocalins of domestic animals and pets have been cloned and their production improved (such as Can f 1, -2, or -4 (37–40)), but methods were also developed for the quantification of the natural allergens to be able to evaluate the exposure levels in different environments, e.g., for Can f 4 (41) which is important for over 80% of people with dog allergies for IgE binding. Such measurements have recently brought up the fact that so-called hypoallergenic dogs shed even higher levels of Can f 1 into homes (29).

Comparing structural features of lipocalins

Lipocalins display a well-known overall similarity in their fold in spite of the relatively low degree of amino acid sequence

identities of below 25% (42). This fold is characterized by a calyx-shaped cavity within the central β -barrel formed by eight antiparallel β -strands βA – βH (in what follows, labels refer to Fig. S1). Loops around the cavity regulate ligand access to the calyx binding site. The extended loop L1 which comprises a $3_{10}(2)$ helix together with hairpin loops L3, L5, and L7 define the top wider end of the barrel, whereas hairpin loops L2, L4, and L6 make the bottom narrower end. This arrangement settles a topology of the β -barrel which is one of the distinctive features of lipocalins. This fold also presents a conserved N-terminal $3_{10}(1)$ helix as well as a medium-size (about 10 residues) conserved α helix H1 and an additional β -strand, βI , near the C-terminal segment. Some lipocalins (e.g., bovine lactoglobulin) display additional secondary structure elements such as a small N-terminal β -strand (β) and a C-terminal $3_{10}(3)$ helix. The presence of one to three structurally conserved regions (SCR1–SCR3) associated to particular local arrangements of strands and helices have been used to divide lipocalins into two structural subfamilies termed kernel lipocalins (those having the three SCRs) and outlier lipocalins (those having a maximum of two SCRs). SCR1 comprises $3_{10}(1)$ and βA in the N-terminal region, SCR2 is composed of sections of βF and βG together with loop L6, and SCR3 is defined by the end of βH together with adjacent residues of H1 in the C-terminal region (Fig. S1). Obviously, amino acid residues in loops L1, L3, L5, and L7 lining the binding site regulate the ligand specificity of lipocalins. Although the name of this protein family makes explicit mention of lipophilic (hydrophobic) compounds, there is a large variety of ligands including amphiphilic molecules or compounds with hydrophobic segments also bearing polar groups that bind to lipocalins.

All these structural similarities observed in these proteins could help to understand IgE cross-reactivities (43) between animal and human lipocalins, and between lipocalins from

Table 2 Organisms with experimental structure of lipocalins available in the Protein Data Bank

Organism	Number of entries	Organism	Number of entries
Eukaryota		Bacteria	
<i>Anguilla japonica</i>	3	<i>Bacillus pumilus</i>	1
<i>Arabidopsis thaliana</i>	2	<i>Bacillus subtilis</i>	1
<i>Argas monolakensis</i>	4	<i>Bacteroides eggerthii</i>	1
<i>Argas reflexus</i>	2	<i>Bacteroides ovatus</i>	1
<i>Bos taurus</i>	37	<i>Bacteroides thetaiotaomicron</i>	2
<i>Canis lupus familiaris</i>	2	<i>Bacteroides uniformis</i>	3
<i>Capra hircus</i>	3	<i>Bradyrhizobium diazoefficiens</i>	3
<i>Coturnix coturnix</i>	1	<i>Enterococcus faecalis</i>	1
<i>Coturnix japonica</i>	2	<i>Escherichia coli</i>	6
<i>Diptera punctata</i>	3	<i>Escherichia coli K-12</i>	2
<i>Equus caballus</i>	1	<i>Helicobacter pylori</i>	1
<i>Homarus gammarus</i>	4	Total	22
<i>Homo sapiens</i>	79		
<i>Lingulodinium polyedrum</i>	1		
<i>Mesocricetus auratus</i>	1		
<i>Mus musculus</i>	34		
<i>Ornithodoros moubata</i>	4		
<i>Ovis aries</i>	2		
<i>Pieris brassicae</i>	5		
<i>Rattus norvegicus</i>	4		
<i>Rhipicephalus appendic</i>	6		
<i>Rhodnius prolixus</i>	68		
<i>Sus scrofa</i>	6		
<i>Trichosurus vulpécula</i>	3		
Total	277		

As of June 22, 2015, the search for 'lipocalin' in the PDB yielded 299 entries distributed between eukaryota and bacteria.

different animals (44–46), although not necessarily correlating with the symptoms.

For instance, in the current view at the amino acid level the dog allergens Can f 1 and Can f 2 correspond to human LCN1 and -2, respectively, whereas the four molecules only share 25% amino acid similarities between them. The amino acid sequences of various animal and human lipocalins LCN1 and -2 are aligned in Fig. 2. Identities above 60% occur between Fel d 4 and Equ c 1, Fel d 4 and Can f 6, Ory c 4, Rat n 1 and Mus m 1, and Can f 1 and Fel d 7.

In contrast, there was no amino acid homology among human LCN2 and any of the analyzed animal lipocalins, only 57% among human LCN1 and Fel d 7, and 56% among LCN1 and Can f 1.

T-cell responses have been found to be 'suboptimal' for Can f 1 (47), although resembling those to human LCN1 (48). Can f 4 T-cell responses were shown to be a Th2-deviated memory response, in part to peptides with promiscuous HLA-binding capacity (49), whereas the DR4-DQ8 haplotype and T-cell receptor Vbeta T-cell subset were indicative for the absence of Can f 1 allergy (50).

The above implies that amino acid sequence identities alone do not sufficiently explain why all lipocalins are important in innate immune regulation, and why they are typically allergenic. The known anti-bacterial activity of the human neutrophil lipocalin LCN2 (NGAL) is caused by the high affinity of this lipocalin for the siderophore-Fe³⁺ complex

and it should be investigated systematically whether from this it can be extrapolated to animal lipocalins. In fact, the molecular ligand transport function of lipocalins and of lipocalin-like proteins could be particularly significant for the Th2 skewing capacity, independent of their mammalian (51) or plant (52) origin. We propose that this feature is likely connected with the similar β -barrel fold in human and animal lipocalins (Fig. 3) (33), as well as with the binding plasticity of their calyx-like cavity able to accommodate a great disparity of substances involved in metabolism and communication (33, 39, 53). Major sources of (at least the human) LCN2 are the liver (54) and macrophages (55), with sphingosin-1-phosphate inducing its production. Lipocalins are elevated and released during inflammation (56), infections (57) and sepsis (58–60), especially when the urinary tract is affected in humans and dogs (61, 62); in cardiovascular inflammation they get overexpressed in the brain and linked with depression (63); in cancer LCN2 is overexpressed (11, 64) prompting interaction with metalloproteinase-9 (MMP-9) (65), but only LCN2 is prognostic (66). In the immunosuppressive environment of the tumor stroma LCN2 cooperates with CCL2 to induce immunoregulatory DCs and subsequently CD4(+)FoxP3(+) Treg cells and supports metastasis (67). Moreover, local IL-10 stimulates tumor infiltrating M2 macrophages to release LCN2 and iron (68, 69). Hence, in cancer the opposite of what is needed in allergy is the problem (70). It is further known that macrophages convert to an

		Cav p 3.0101	Mes a 1.0101	Cav p 2.0102	Bos d 2.0101	Can f 4.0101	Equ c 1.0101	Fel d 4.0101	Can f 6.0101	Ory c 4.0101	Cav p 6.0101	Mus m 1.0101	Rat n 1.0101	Can f 1.0101	Fel d 7.0101	human LCN1	Can f 2.0101	Bos d 5.0101	human LCN2
F0UZ12	Cav p 3.0101	100	43	43	38	32	25	25	23	23	21	24	24	17	17	18	19	12	13
Q9QXU1	Mes a 1.0101	43	100	35	34	32	27	26	26	23	23	21	24	20	17	20	17	16	12
F0UZ11	Cav p 2.0102	43	35	100	38	32	29	30	24	30	22	28	30	18	17	20	14	16	12
Q28133	Bos d 2.0101	38	34	38	100	31	29	28	26	26	22	22	25	17	16	14	16	16	14
D7PBH4	Can f 4.0101	32	32	32	31	100	24	25	25	32	23	26	28	16	18	16	21	13	15
Q95182	Equ c 1.0101	25	27	29	29	24	100	69	57	52	47	45	48	24	23	24	24	19	16
Q5VFH6	Fel d 4.0101	25	26	30	28	25	69	100	69	63	54	49	57	24	20	22	25	23	16
H2B3G5	Can f 6.0101	23	26	25	26	25	57	69	100	58	53	45	52	22	23	21	24	20	19
U6C8D6	Ory c 4.0101	23	23	30	26	32	52	63	58	100	49	51	54	20	22	23	29	18	16
S0BDX9	Cav p 6.0101	21	23	22	22	23	47	54	53	49	100	45	50	19	21	18	26	22	18
P02762	Mus m 1.0101	24	21	28	22	26	45	49	45	51	45	100	64	17	18	18	26	15	16
P02761	Rat n 1.0101	24	24	30	25	28	48	57	52	54	50	64	100	19	22	20	28	23	17
O18873	Can f 1.0101	17	20	18	17	16	24	24	22	20	19	17	19	100	63	56	20	24	18
E5D225	Fel d 7.0101	17	17	17	16	18	23	20	23	22	21	18	22	63	100	57	21	27	20
P31025	human LCN1	18	20	20	14	16	24	22	21	23	18	18	20	56	57	100	18	24	14
O18874	Can f 2.0101	19	17	14	16	21	24	25	24	29	26	26	28	20	21	18	100	18	13
P02754	Bos d 5.0101	12	16	16	16	13	19	23	20	18	22	15	23	24	27	24	18	100	16
P80188	human LCN2	13	12	12	14	15	16	16	19	16	18	16	17	18	20	14	13	16	100

>60%
 50-60%
 40-50%

Figure 2 Comparison of human lipocalins and major animal lipocalin allergens. Amino acid identities (%) between mammalian lipocalin allergens and human lipocalin 1 and 2 were determined with Clustal Omega via <http://www.ebi.ac.uk/Tools/msa/clustalo/>. High-

lighted regions show identities higher than 40%. The different gray shades illustrate the levels of amino acid identities. Amino acid sequences were retrieved from UniProtKB database (<http://www.uniprot.org/uniprot/>).

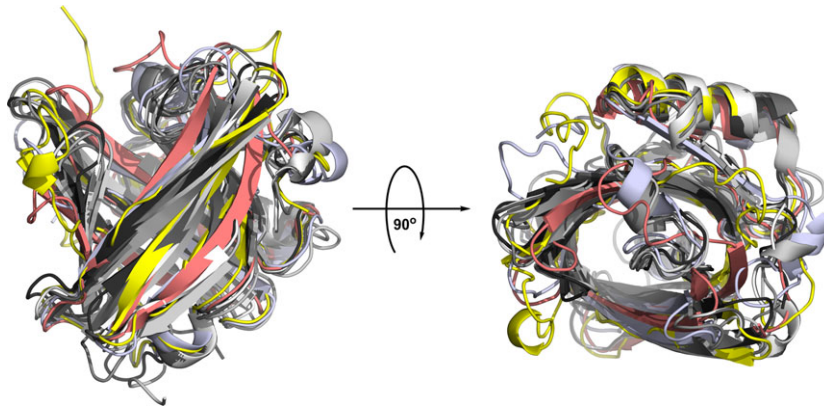


Figure 3 Symphony of human and animal lipocalins by structural superimposition. Human LCN2 and LCN1 lipocalins are colored yellow and salmon, respectively, Bos d 5 is colored blue white and

the remaining lipocalins in Fig. 1 are colored in different shades of gray from white (Equ c 1) to black (Mus m 1). The rotated image on the right gives an upper view of the calyx-like cavity.

anti-inflammatory type by IL10 and glucocorticoid stimulation (71). Alternatively activated macrophages further regulate the immune response by secreting LCN2, which is directly linked with IL10 formation (and in our own hands glucocorticoid release). Taken together, lipocalins are regarded as biomarkers for several diseases (72) and are at the crossing point between immunity and tolerance that is of particular interest for allergen immunotherapy.

The secret function of lipocalins determined by their pocket load

Some important human lipocalins are considered acute phase proteins with innate immune function, especially against

gram-negative bacteria. Their growth depends on iron, which they secure via the secretion of a bacterial siderophore, [= a high-affinity iron acquisition molecule], like enterobactin, an iron-specific chelating agent closely related to the ligand in the crystal structure of human LCN2 displayed in Fig. 1. We speculate that, like LCN2 which withdraws iron from bacteria by accepting it into their own pocket, also some of the other mammalian lipocalins may act bacteriostatically (Fig. 3) (73). On the other side of this evolutionary interplay, bacterial siderophores can inhibit the function of neutrophil myeloperoxidase and enhance the bacterial survival (74), or simply overwhelm the lipocalin defense system (75). A lipocalin-2 receptor (termed 24p3/NGAL) and Lipoprotein Receptor-Related Protein have been described binding LCN in

humans and rodents (65, 76), possibly also involving MMP9 in a triple interaction.

Less attention has been given to a potentially differential immune function of lipocalins depending on the load state of their pocket, either holo – full, or apo – empty. Interestingly, the major birch pollen allergen Bet v 1 has a relation to bacterial proteins (77) by its old scaffold and a central pocket, which was predicted to bind quercetin-3-*O*-sophoroside (78). However, the flavonoid quercetin also behaves as a siderophore (52). By means of an *in silico* approach using flexible docking calculations and geometry optimizations we were able to analyze the optimal binding of human LCN2 to several siderophore-iron complexes with 1, 2, or 3 catechol chelating moieties (79). This study allowed us to estimate protein-ligand dissociation constants in the micro- to nanomolar range indicative of a high affinity that arises to a great extent from the electrostatic interactions between amino acid residues surrounding the outer part of the cup-like cavity and polar groups of the siderophore (79). A further illustration of this optimal binding is depicted in Fig. 4 where the model complex between hLCN2 and a hexadentate iron chelator, Fe(DHBA)₃, is shown. Note that the presence of hydrophobic moieties and polar groups in the ligand is consistent with the presence of hydrophobic residues together with charged (mainly basic) side chains in the protein that produce the electrostatic effects largely responsible for this efficient protein-ligand binding. However, we emphasize that more experimental studies have to be under-

taken not only to approve our estimation with certainty *in vitro*, but also to be able to extrapolate to other lipocalin allergens.

More importantly, the load of this binding pocket is decisive for the immunomodulatory function of lipocalins. Only the apo-form of lipocalin Bos d 5 and lipocalin-like allergen Bet v 1 (51, 52) promoted the survival of CD4⁺ T cells and IL-13 production in human PBMCs, whereas the holo-form was nonallergenic, so far at least *in vitro*. Consistent with this function, the loading state of brain lipocalin is decisive for the survival of neuronal cells (80). Furthermore, in a dose-dependent loading approach, holo-LCN2 had the highest capacity to induce HLA-G(+)/FoxP3(+) T-regulatory cells (81). Therefore, it may be anticipated that exogenous lipocalins, animal allergens, may be tolerated rather than inducing allergy, when complexed with ligands.

Synopsis

Humans and their domestic animals share molecules that play a role both physiologically in innate immunity, and pathologically as allergens. Whereas many important animal allergens relevant for humans belong to the lipocalin family, it is not known yet whether *vice versa* human lipocalins may act as allergens for pet animals. It is not by accident that the lipocalin fold is highly conserved in the animal kingdom. It allows lipocalins to withdraw iron from microbes into their molecular pocket and thereby act bacteriostatic.

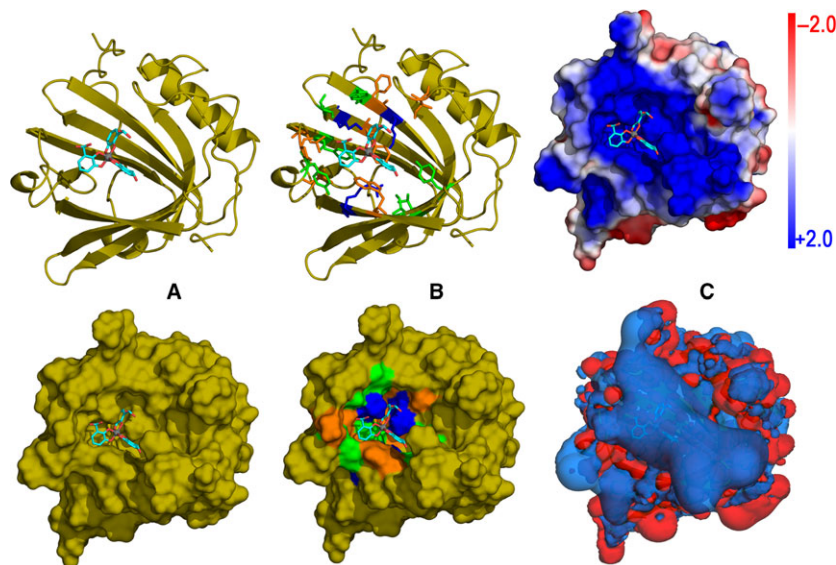


Figure 4 Prototypic of lipocalin-siderophore binding: model complex of human LCN2 and Fe(DHBA)₃, a hexadentate iron-chelator. The siderophore (DHBA = 2,3-dihydroxybenzoic acid) is depicted as sticks with carbons in cyan, oxygens in red, and Fe³⁺ ion as a gray sphere. (A) Geometry of the siderophore in the cup-like cavity (top) and the corresponding protein surface showing the topography of the pocket (bottom). (B) Residues within a 5 Å distance from the ligand color-coded as follows: basic = blue, polar = green, and nonpolar = orange. Top: ribbon and sticks

diagram. Bottom: the corresponding color-coded surface. (C) Poisson–Boltzmann (PB) electrostatic potential of hLCN2. Top: PB potential mapped onto the protein surface according to the scale indicated in the bar. The strongly positive electrostatic nature of the pocket area stabilizes the electrically negative oxygenated groups in the siderophore. Bottom: +2 (blue) and -2 (red) 3D isosurfaces of the PB electrostatic field created by hLCN2. A large positive isosurface covers the cavity area in which the siderophore is accommodated.

In conclusion lipocalins may, independent of their mammalian other animal, or plant origin, house siderophore ligands, which critically determine their innate immunomodulatory as well as allergenic characteristics. It has been shown that in loaded state human lipocalins induce regulatory T cells, whereas empty lipocalins rather promote Th2 responses and inflammation. To this end, the interplay between exogenous lipocalins and human LCNs is not resolved, but it is tempting to speculate that they interfere with each other either via receptor binding or via capturing each other's iron ligand.

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Author contributions

Jensen-Jarolim E responsible for scientific concept, writing of the manuscript, and literature search. Pacios Luis F per-

formed calculations, computer modeling, and structural alignments of all structures of this study (Figs 1, 3 and 4). Bianchini R and Hofstetter G involved in amino acid sequence searches and comparisons and contributed to the writing of the manuscript; Hofstetter G also contributed to the design of Fig. 2. Pacios, LF, and Roth-Walter, F contributed to the overall scientific concept and writing of the manuscript.

Conflicts of interest

Erika Jensen-Jarolim, Luis F. Pacios and Franziska Roth-Walter declare that they are inventors on PCT/EP2015/050126. Rodolfo Bianchini and Gerlinde Hofstetter declare no conflict of interest.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. 3D structure and topology of a prototypical lipocalin.

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