Endogenous anti-inflammatory neuropeptides and pro-resolving lipid mediators: a new therapeutic approach for immune disorders

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Abstract

Identification of the factors that regulate the immune tolerance and control the appearance of exacerbated inflammatory conditions is crucial for the development of new therapies of inflammatory and autoimmune diseases. Although much is known about the molecular basis of initiating signals and pro-inflammatory chemical mediators in inflammation, it has only recently become apparent that endogenous stop signals are critical at early checkpoints within the temporal events of inflammation. Some neuropeptides and lipid mediators that are produced during the ongoing inflammatory response have emerged as endogenous anti-inflammatory agents that participate in the regulation of the processes that ensure self-tolerance and/or inflammation resolution. Here we examine the latest research findings, which indicate that neuropeptides participate in maintaining immune tolerance in two distinct ways: by regulating the balance between pro-inflammatory and anti-inflammatory factors, and by inducing the emergence of regulatory T cells with suppressive activity against autoreactive T-cell effectors. On the other hand, we also focus on lipid mediators biosynthesized from ω-3 and ω-6 polyunsaturated fatty-acids in inflammatory exudates that promote the resolution phase of acute inflammation by regulating leukocyte influx to and efflux from local inflamed sites. Both anti-inflammatory neuropeptides and pro-resolving lipid mediators have shown therapeutic potential for a variety of inflammatory and autoimmune disorders and could be used as biotemplates for the development of novel pharmacologic agents.

Keywords: inflammation ♦ autoimmunity ♦ regulatory T cells ♦ tolerance ♦ lipid mediators ♦ lipoxins ♦ neuropeptide ♦ resolvins

Introduction

Immune tolerance: a matter of life or death

The immune system responds to pathogen invasion with two temporally separate but physically linked responses, mediated by different types of cells. The first response, termed innate immunity, involves neutrophils, monocytes/macrophages and dendritic cells (DCs) in the periphery and microglia in the central nervous system (CNS). The innate response is rapid and based on the recognition of conserved pathogen-associated molecular patterns. In contrast, the adaptive response occurs later, following activation of T and B...
lymphocytes through specific receptors. In contrast to the innate response, adaptive immunity leads to the development of memory for a specific antigen.

The successful elimination of most pathogens requires crosstalk between the innate and adaptive arms of the immune system. The innate immune system recognizes pathogen-associated molecular patterns through pattern-recognition receptors, such as Toll-like receptors (TLRs), which induce the release of pro-inflammatory cytokines, chemokines and free radicals, recruitment of inflammatory cells to the site of infection, and lysis of infected host cells by natural killer cells and cytotoxic T lymphocytes. The inflammatory process is vital to the survival of all complex organisms, and its functions play a profound role in health and disease. Although it is a localized protective response that serves to destroy the injurious agent, once the pathogen is eliminated, cells participating in innate and adaptive immunity have to be deactivated or eliminated, to re-establish tissue homeostasis. The accumulation and subsequent activation of leucocytes are central events in the pathogenesis of virtually all forms of inflammation. Uncontrolled activation of the immune system and the sustained production of inflammatory mediators lead to serious consequences for the host, such as tissue destruction, organ failure, even death. A further damage arises from potential autoimmune responses occurring during the inflammatory response, in which the immune cells and molecules that respond to pathogen-derived antigens can also react to self-antigens. Therefore, in inflammatory/autoimmune diseases like multiple sclerosis, rheumatoid arthritis, and type 1 diabetes, the initial stages involve multiple steps that can be divided into two main phases: early events associated with initiation and establishment of autoimmunity to self-tissue components in peripheral lymphoid organs, and later events associated with the evolving immune and destructive inflammatory responses in the target tissue (Fig. 1) [1, 2]. Progression of the autoimmune response involves the development of self-reactive T helper 1 (Th1) and Th17 cells, their entry into the target tissue, release of pro-inflammatory cytokines and chemokines and subsequent recruitment and activation of inflammatory cells (macrophages, neutrophils and mast cells). Production of inflammatory mediators, such as cytokines, matrix-degrading enzymes and free radicals by infiltrating cells and resident cells (synovial fibroblasts, osteoclasts, microglia cells) damages self-tissues. In addition, Th1-mediated production of autoantibodies by B cells, which form immune complexes and activate complement and neutrophils, contributes to autoimmune pathology and disease propagation [2].

**How to solve the problem of excessive inflammation: to counterbalance or to resolve**

It is apparently clear that safe induction of antigen-specific long-term tolerance is critical for the control of autoreactive T cells on autoimmune diseases. In addition, the inflammatory process needs to be limited since excessive responses result in severe inflammation and collateral tissue damage. In general, inflammatory responses are self-controlled by anti-inflammatory mediators secreted by host innate immune system during the ongoing process, and the ability to control an inflammatory state depends on the local balance between pro- and anti-inflammatory factors [3]. Moreover, adaptive immune system also helps to maintain immune tolerance during infection-induced immunopathology [4]. Intrinsic control of lymphocytes is exerted for example by central clonal deletion of self-reactive T cells in the thymus via apoptosis of immature self-reactive lymphocytes upon the exposure to self-antigen or activation-induced cell death of mature effector cells. Moreover, recent evidence demonstrate that the generation of antigen-specific regulatory T cells (Treg) with suppressive activity plays a critical role in the induction of peripheral tolerance (Fig. 1). For example, depletion of CD4+CD25+ Treg cells produces autoimmune disease in otherwise normal animals, and their reconstitution prevents disease [4, 5]. In addition, Treg cells have been shown to be deficient in patients with rheumatoid arthritis, multiple sclerosis, type-1 diabetes and other autoimmune diseases [6–8]. Moreover, numerous studies have demonstrated the therapeutic use of antigen-specific Treg cells in various models of autoimmune disorders [3–5].

From a therapeutic point of view, the fact that the appearance of exacerbated inflammatory and autoimmune diseases is a consequence of an unbalance in pro-inflammatory factors versus anti-inflammatory cytokines, or in self-reactive Th1 cells versus Treg cells, becomes critical to the identification of agents that restore self-tolerance by regulating both unbalanced inflammatory and autoreactive responses. Non-steroidal anti-inflammatory, steroid and antihistaminic compounds, for instance, were developed on this basis. Because maintenance of immune tolerance is essential for survival, it is plausible to suppose that immune cells might produce endogenous anti-inflammatory factors during the inflammatory/autoimmune response in an attempt to maintain it under control. Numerous researchers have concentrated their efforts investigating traditional immunosuppressive cytokines, such as IL-10, IL-13 and TGF-β1 [9]. However, others have focused their search in neuropeptides and hormones, classically considered as neuroendocrine mediators, but which are also produced by immune cells, especially under inflammatory conditions [10, 11].

Similarly, the resolution phase of acute inflammation has emerged as a new terrain for drug design and resolution-directed therapeutics [12–15]. Resolution of inflammation is an active regulated program that is required for the return from inflammatory disease to health and tissue homeostasis. This event is accompanied by lipid mediator class switching from pro-inflammatory prostaglandins (PGs) and leukotrienes (LT) to the biosynthesis of anti-inflammatory agents, such as lipoxins (LXs), and the newly described pro-resolving mediators synthesized in inflammatory exudates from ω-3 polyunsaturated fatty-acid (PUFA) precursors, resolvins and protectins [12–15].

In this review, we propose a platform for the pharmacologists to develop novel therapeutics based on endogenous agents that not only simply block what initiates and drives inflammation, but also restore immune tolerance and/or resolve the problem.
Anti-inflammatory neuropeptides and pro-resolving lipid mediators emerge as a new strategy to manage inflammation-based diseases.

Tuning immune tolerance with anti-inflammatory neuropeptides

Neuropeptides as biochemical mediators in nervous-immune communication

For many years, the neuroendocrine system and the immune system have been considered as two autonomous networks functioning to maintain a balance between host and environment. The neuroendocrine system responds to external stimuli such as temperature, pain and stress, whereas the immune system responds to exposure to bacteria, viruses and tissue trauma. However, in the last 20 years, we have come to realize that both systems mount a variety of coordinated responses to danger. Acting as a ‘sixth sense’, the immune system signals the brain to respond to the ‘danger’ of pathogen infection and inflammation, resulting in the orchestration of the febrile response and its subsequent effects on behaviour, including sleep, appetite and feeding [16]. Conversely, the immune system is regulated by the CNS, in response to environmental stress, either directly by the autonomic nervous system or by way of the hypothalamus-pituitary-adrenal (HPA) axis. This intimate bi-directional network is based on the fact that the immune and neuroendocrine systems share ligands such as neuropeptides, hormones, cytokines and the respective receptors. Therefore, it is reasonable to suggest that factors produced by the neuroendocrine system could contribute to the immune tolerance maintenance. Glucocorticoids and norepinephrin are the classical examples of endogenous immunosuppressive agents produced by the HPA axis and the sympathetic nervous system, respectively, in response to stress or systemic inflammation [16, 17].

Furthermore, various neuropeptides are released at the peripheral endings of sensory and efferent nerves in close proximity to immune cells in response to various invasive and inflammatory stimuli. The antinociceptive and anti-inflammatory effect of opioids released during neurogenic inflammation is the oldest example in this field [18]. From the growing list of neuropeptides currently thought to possess immunomodulatory actions (~50), some neuropeptides have lately emerged as potential candidates to treat the unwanted immune responses that occur in inflammatory and autoimmune disorders, by tuning immune homeostasis in a cytokine-like manner. In this review, we focus on the most recent developments regarding the effects on immune tolerance of some well-known anti-inflammatory neuropeptides and we highlight the effectiveness of using these neuropeptides in treating several immune disorders. The therapeutic effects of these neuropeptides on immune disorders have been classically attributed to their dual capacity to down-regulate the inflammatory response and to inhibit antigen-specific T helper 1 (Th1)-driven responses [12]. Furthermore, recent data suggest that some of them might facilitate immune homeostasis through a newly discovered mechanism involving the generation of Treg cells.

Vasoactive intestinal peptide (VIP), α-melanocyte stimulating hormone (αMSH), urocortin, adrenomedullin, cortistatin and ghrelin are neuropeptides belonging to different families of peptides that show no homology among them [19–24] (Table 1). Their major cellular sources and the physiological roles that they play in the organism are very different (Table 1). Apparently these neuropeptides look very different, but they share certain characteristics that make them attractive for immune tolerance. First, they are produced by immune cells (Table 1), especially under inflammatory conditions, or following antigenic stimulation [25–31]. Second, they bind to G-protein-coupled receptors (GPCRs) expressed in different immune cells, including T cells, macrophages, monocytes, DCs and neutrophils [25, 28, 29, 32–39]. Third, they mainly signal through the activation of cAMP/protein kinase A (PKA) pathway [24, 25, 29, 40–42], which is considered as an immunosuppressive signal [43, 44]. Through the elevation of intracellular
### Table 1. Anti-inflammatory neuropeptides: expression and functions

| Neuropeptide sequence          | Peptide family | Main source | Immune source | Main actions | Receptor type | Receptor in immune cells |
|-------------------------------|----------------|-------------|---------------|--------------|---------------|--------------------------|
| VIP HSDAVFTDNYT               | PACAP secretin| GI, CNS, heart, lung, thyroids, kidney, genital | CD4 Th2, CD8, PMN, Mast cells | vasodilation, ↑cardiac output, bronchodilation, hyperglycemia, smooth muscle relaxation, ↑growth, hormonal regulation, analgesia, hypertermia, neurotrophic effects, learning and behaviour, bone metabolism, GI secretion, gastric motility | VPAC1 | T, M, Mo, DC, PMN |
| αMSH SYSEMEJRFWG             | POMC ACTH     | CNS, pituitary, skin | T, Mo, DC | skin-darkening effects, learning, attention and memory, motor effects, ↓food intake | MC1R | T, M, Mo, DC, PMN, NK, B |
| Urocortin DNPSLSIDLTFHLLRTL | CRH urotensin | CNS, pituitary, GI, testis, heart, skin, kidney | T, B, M, Mo, Mast cells | vasodilation, bronchodilatation, ↑cardiac output, smooth muscle relaxation, ↓food intake, ↑ACTH secretion | CRFR2 | T, M, Mo, DC, PMN |
| Adrenomedullin YROSMNIFQGLRF [CRFGTC]TVQKL | calcitonin CGRP | adrenal, CNS, all peripheral tissues with the exception of thyroid | M, Mo | vasodilation, bronchodilatation, ↑cardiac output, smooth muscle relaxation, ↓food intake, ↑ACTH secretion | CRLR-RAMP2/3 | T, M, Mo, DC |
| Cortistatin DRMP[KCNFWKTFSSC]K-NH2 | SOM | CNS, kidney, stomach | T, Mo, M | ↓locomotor activity, ↑slow-wave sleep, ↓growth hormone, ↓cell proliferation | Sst1-5 | T, M, Mo, DC |
| Ghrelin GSSFLSPEHQ         | motilin       | CNS, GI, stomach, pancreas | Mo, M | ↑cardiac output, ↑appetite and adiposity, ↑growth hormone, vasodilatation, ↑GI secretion, ↑gastric motility | GHSR | T, M, Mo, DC |

**Abbreviations:** calcitonin gene-related peptide, CGRP; proopiomelanocortin, POMC; adrenocorticotropic, ACTH; pituitary adenylate cyclase-activating polypeptide, PACAP; growth hormone-releasing hormone, GHRH; corticotropin-releasing hormone, CRH; somatostatin, SOM; central nervous system, CNS; gastrointestinal tract, GI; T cells, T; macrophage, M; Monocyte, Mo; dendritic cell, DC; polymorphonuclear cell, PMN; B cells, B; melanocortin receptors, MCR; somatostatin receptors 1–5, sst1–5; ghrelin receptor, GHSR; calcitonin-related ligand receptor, CRLR; CRH receptor, CRFR; VIP/PACAP receptor, VPAC; receptor-activity-modifying proteins, RAMP; growth hormone-secretagogue receptor, GHSR.

**Amino acid sequences correspond to human peptides. Disulphite bridges between cysteins on adrenomedullin and cortistatin sequences are shown in parenthesis.**

**Family of peptides showing some homology in sequence/structure with the referenced neuropeptides.**

**Tissues and organs producing significant levels of the different neuropeptides.**

**Immune cells that produce anti-inflammatory neuropeptides.**

**Major physiological roles of the neuropeptides in different tissues/organisms of the body. ↓, indicates inhibition. ↑, indicates stimulation.**

**Immune cells expressing the different neuropeptide receptor subtypes.**
cAMP, these neuropeptides down-regulate the activation of several transduction pathways and transcription factors essential for the transcriptional activation of most of the inflammatory cytokines, chemokines and costimulatory factors, including the nuclear factor-κB (NF-κB), mitogen-activated protein kinases (MAPK), the interferon regulatory factor 1 (IRF1) and the activator protein 1 (AP1) [25, 28, 45]. Some evidence indicate that VIP and αMSH could also affect common upstream elements located very early in the signalling of these pathways, such as inhibition of the expression of TLRs and associated proteins [46–49].

**Beneficial effect of neuropeptides in inflammatory disorders**

Recent studies examining these neuropeptides have shown their relevance to health, proving a potentially crucial clinical significance in inflammatory and autoimmune diseases that upset the balance of body systems (Fig. 2). Treatment with VIP, αMSH, urocortin, adrenomedullin, cortistatin or ghrelin decreases the frequency, delays the onset and reduces the severity of various experimental models of sepsis [39, 50–55], collagen-induced arthritis [56–60], inflammatory bowel disease [61–65], type I diabetes mellitus [66, 67], multiple sclerosis [68–70], Sjogren’s syndrome [71], pancreatitis [72, 73] and uveoretinitis [74, 75]. The therapeutic effects of these neuropeptides are associated with the reduction of the two main phases of these diseases. They impair early events that are associated with the initiation and establishment of autoimmunity to self-tissue components, as well as later phases that are associated with the evolving immune and destructive inflammatory responses. These neuropeptides reduce the development of self-reactive TH1 cells, their entry into the target organ, the release of pro-inflammatory cytokines and chemokines and the subsequent recruitment and activation of macrophages and neutrophils. This results in a decreased production of destructive inflammatory mediators (cytokines, nitric oxide, free radicals and matrix metalloproteinases) by infiltrating and resident (i.e. microglia or synoviocytes) inflammatory cells. In addition, the inhibition of the self-reactive TH1-cell responses gives to decreased titters in IgG2a autoantibodies, an antibody subtype that activates complement and neutrophils and contributes to tissue destruction.

**Neuropeptides counterbalance the inflammatory response**

The anti-inflammatory action of these neuropeptides is exerted at different levels of the innate immunity (Fig. 2): (1) inhibition of phagocytic activity, free radical production, adherence and migration of macrophages [33, 36, 76]; (2) reduction in the production of inflammatory cytokines (TNFα, IL-12, IL-6 and IL-1β) and various chemokines and down-regulation of the expression of inducible nitric oxide synthase and cyclooxygenase 2 (COX2) and the subsequent release of nitric oxide and prostaglandin E2 by macrophages, DCs and microglia [25, 28, 30, 35, 37, 39, 50, 51, 61, 62, 65, 78–88]; (3) stimulation of the production of anti-inflammatory cytokines such as IL-10 and IL-1Ra [39, 50, 51, 61, 89, 90]; (4) decrease in the co-stimulatory activity of antigen-presenting cells (APCs) for antigen-specific T cells by down-regulating the expression of the co-stimulatory molecules [91, 92]; (5) reduction of the secretion of late inflammatory mediator high-mobility group box 1 [93, 94]; (6) inhibition of mast cell degranulation [55]; (7) induction of apoptosis in macrophages [95] and (8) induction of the anti-inflammatory transcription factor, peroxisome proliferator-activated receptor-γ (PPAR-γ) [96].

**Neuropeptides down-regulate Th1 responses**

Although the mechanisms involved in the suppressive effects on TH1-cell responses of most of these neuropeptides are not fully elucidated, most data coming from VIP studies have clearly demonstrated that neuropeptides regulate the TH1/TH2 balance through various non-excluding mechanisms involving both direct actions on differentiating T cells and indirect regulation of APC functions (Fig. 2) [67, 77, 97–102]. First, VIP inhibits the production of the TH1-associated cytokine IL-12. Second, VIP induces CD86 expression in resting murine DCs, which is important for the development of TH2 cells. Third, VIP has been shown to promote specific TH2-cell recruitment by inhibiting CXC-chemokine ligand 10 (CXCL10) production and inducing CC-chemokine ligand 22 (CCL22) production, two chemokines that are involved in the homing of TH1 cells and TH2 cells, respectively. Fourth, VIP inhibits CD95 (FasL)- and granzyme B-mediated apoptosis of mouse TH2 but not of TH1 effector cells. Finally, VIP induces the TH2 master transcription factors c-MAF, GATA-3 and JUNB in differentiating murine CD4+ T cells, and inhibits T-bet, which is required for TH1-cell differentiation.

**Neuropeptides generate regulatory T cells**

Finally, the generation of Treg cells has been recently found to play a major role in the beneficial effect of these neuropeptides in autoimmunity (Fig. 2). They induce the peripheral expansion of new antigen-specific CD4+CD25+ forkhead box P3 (FOXP3)+ T regulatory cells, with suppressive activity on self-reactive T cells [47, 59–62, 65, 74, 103–105]. The suppressive mechanism is mediated through direct cellular contact that is mainly dependent on cytotoxic T lymphocyte-associated protein 4 (CTLA4), or through the production of the immunosuppressive cytokines IL-10 and/or TGFβ. In addition, VIP and αMSH have been found to generate DCs with a tolerogenic phenotype, characterized by their ability to induce CD4 and CD8 regulatory T cells [91, 106–108]. The involvement of Treg cells in the beneficial effect of these neuropeptides on autoimmunity is supported by the fact that the in vivo blockade of the Treg-cell mediators CTLA4, IL-10 and TGFβ1 significantly reversed their therapeutic action [57, 59, 60, 103, 104]. Therefore, the generation of Treg cells by neuropeptides could...
Fig. 2 Control of immune tolerance by anti-inflammatory neuropeptides. Vasoactive intestinal peptide (VIP), α-melanocyte-stimulating hormone (αMSH), urocortin (UCN), adrenomedullin (AM), ghrelin (GHR) and cortistatin (CST) are produced by T cells or macrophages in response to antigenic and inflammatory stimulation. These neuropeptides induce immune tolerance and inhibit the autoimmune response through different non-excluding mechanisms. (A) They decrease Th1-cell functions through direct actions on differentiating T cells, or indirectly by regulating dendritic cell (DC) functions. As a consequence, the inflammatory and autoimmune responses are impaired because the infiltration and activation of neutrophils and macrophages by interferon-γ (IFN-γ) and the production of complement-fixing IgG2a antibodies are avoided. (B) Neuropeptides inhibit the production of inflammatory cytokines, chemokines, free radicals (i.e., nitric oxide) and high-mobility group box 1 (HMGB1) by macrophages and microglia. In addition, they impair the costimulatory activity of macrophages on effector T cells, inhibiting the subsequent clonal expansion. This avoids the infiltration of leucocytes and the inflammatory response and the subsequent cytotoxicity against the target tissue. (C) Neuropeptides induce the new generation of regulatory T cells (Treg) that suppress activation of autoreactive T cells through a mechanism that involves production of interleukin-10 (IL-10) and transforming growth factor-β (TGFβ), and/or expression of the cytotoxic T lymphocyte-associated protein 4 (CTLA4). In addition, neuropeptides indirectly generate Treg through the differentiation of tolerogenic DCs. This effect contributes to the maintenance of an anti-inflammatory state and restores the immune tolerance. Black arrows indicate a stimulatory effect. Red crosses indicate an inhibitory effect.
explain the selective inhibition of Th1 immune responses once T cells have completed differentiation into Th1 effector cells, as demonstrated by the therapeutic effect of delayed administration of these neuropeptides in established arthritis, EAE and diabetes.

Are endogenous neuropeptides important for maintaining immune tolerance in the body?

Of physiological relevance is the presence of these neuropeptides in barrier organs like skin and mucosal barriers of the gastrointestinal, genital and respiratory tracts suggests that they may be key components of the innate immune system (Table 1). Indeed, (MSH, ghrelin and adrenomedullin have shown antimicrobial properties [94, 109, 110]. The relevance of these neuropeptides as natural anti-inflammatory factors is also supported by results obtained in several inflammatory models performed in animals that are deficient for any of these neuropeptides or their receptors. For example, mice that lack VIP or its receptor show higher systemic inflammatory responses and are more susceptible to die by septic shock [111, 112], and VIP receptor-deficient mice have increased Th1-type responses (i.e. delayed-type hypersensitivity), whereas mice that overexpress VIP receptors show eosinophilia, high levels of IgE and IgG1 and increased cutaneous anaphylaxis (typical Th2-type responses) [113–115]. Moreover, an altered expression of VIP receptors in T cells has been related to aberrant Th1 immunity in patients with multiple sclerosis and rheumatoid arthritis [116–118]. In addition, it has been recently found in a genetic association between multiple-marker haplotypes of VIP receptor and rheumatoid arthritis susceptibility [117]. Finally, the significant reduced levels of VIP found in patients with lupus and autoimmune thyroiditis have been related to the existence of high amounts of autoantibodies with VIPase activity [119]. These findings support the notion that reduced levels of neuropeptides, and deficiencies and/or mutations in their receptors and signalling make us more susceptible to suffer inflammatory and autoimmune diseases.

Resolution of inflammation by endogenous lipid mediators

Human beings depend on the nutritional supply of two types of essential PUFAs, ω-3 and ω-6, which are enriched in fish oils. They are precursors of lipid mediators critical for a variety of cellular functions, including inflammation, nociception, renal function, reproductive activity, haemodynamics and blood clotting [120]. Most of the studies in the past were focused on the ω-6 PUFA arachidonic acid (AA) as a classic precursor of bioactive PGs and LTs locally produced after tissue injury, microbical infection and surgical trauma through pathways involving cyclooxygenases (COX-1 and COX-2) and lipooxygenases (LOX). AA-derived lipid mediators such as PGE2, PGD2 and L Ts generated in the initial phase of inflammation have been classically involved in pro-inflammatory signalling and implicated in the pathogenesis of various inflammatory diseases [120, 121]. However, recent studies in animal models have proposed that they can also stimulate circuits to resolution of inflammation.

Lipoxins

Both PGE2 and PGD2 activate the expression of 15-LOX in neutrophils, which switches the mediator profile of these cells from LTB4 to lipoxins [122]. Lipoxins were the first mediators identified to have both anti-inflammatory and pro-resolving activities [123]. Lipoxins (LXA4 and LXB4) are synthesized by transcellular metabolism of AA by LOX/LOX interaction of infiltrating neutrophils with endothelial cells, fibroblasts and platelets in localized in the inflammatory exude (Fig. 3). In addition, lipoxins can be synthesized in an alternative and interesting way. Acetylation of COX-2 by aspirin modifies the enzyme so that it can act as a LOX, which synthesizes the lipoxin precursor 15-hydroxyeicosatetraenoic acid (15-HETE) from AA. By the action of leucocyte 15-LOX, 15-HETE is then transformed in the so-called aspirin-triggered lipoxins (ATLs) 15-epi-lipoxin A4 or 15-epi-lipoxin B4, which show even more potent anti-inflammatory effects than LXA4 (Fig. 3).

Lipoxins and ATLs promote the resolution of inflammation by selectively stopping the entry of new PMNs to sites of inflammation that includes inhibition of chemotaxis of PMNs and their adhesion to and transmigration through endothelial cells and reduction of vascular permeability [122–125]. At the same time, lipoxins and ATLs stimulate the recruitment of monocytes by stimulating their chemotaxis and adherence without causing release of reactive oxygen species [126–128], and promote the non-phlogistic phagocytosis of apoptotic neutrophils by macrophages [129, 130]. This is supported by a shift to an anti-inflammatory response by these mediators, because lipoxin, ATLs and their stable analogues inhibit the production and action of chemokines (i.e. IL-8) and TNFα, whereas stimulate the anti-inflammatory cytokine TGFβ [128, 131]. These effects seem to be mediated through the GPCR, LXA4 receptor (ALXR) also referred to as formyl peptide receptor-like 1 (FPRL1) and the subsequent inactivation of the transactivating pathways NFκB and AP1 [127, 129].

As a consequence, these lipid mediators have been proven effective in various models of inflammatory diseases such as ischemia/reperfusion injury, inflammatory bowel disease, glomerulonephritis, allergic pleural edema, periodontitis, dermal inflammation and cystic fibrosis [131, 132]. Importantly, some of the beneficial effects ascribed to aspirin in various human diseases should be a consequence of the generation of ATL and subsequent promotion of inflammation resolution.

Resolvins and protectins

Recent evidence have demonstrated that AA is not the only fatty-acid substrate that can be transformed by COXs and LOXs to bioactive mediators with roles in anti-inflammation and resolution. The
Fig. 3 Role of new PUFA-derived lipid mediators in the progression and resolution of acute inflammation. A schematic of the biosynthetic pathways for lipid mediators derived from ω-6 (AA, arachidonic acid) and ω-3 (EPA, eicosapentanoic acid; DHA, docosahexaenoic acid) with key enzymes is shown. AA is metabolized by cyclooxygenase 1 (COX1) or COX2 to prostaglandin (PG) G2 and then PGH2, which in turn serves as a substrate for a series of downstream synthases to give rise to the PGs. PGs (such as PGD2) and leucotrienes (LTB4) participate in the initiation of the inflammatory response. PGH2 is also metabolized to PGD2 and then broken down to PGJ2 and the cyclopentenone PGs (cyPGs), which act as anti-inflammatory factors. After the initiation of acute inflammation by PGs and LTs, a class switching occurs with time towards pro-resolving lipid mediators that start with the generation of lipoxins (LXs) from AA through three distinct biosynthetic routes. First, AA is sequentially metabolized in a transcellular manner by 5-lipoxygenase (5-LOX) in polymorphonuclear cells (PMNs) and platelet 12-LOX to lipoxin A4 (LXA4) and LXB4. Second, AA can be transformed via sequential actions of the 5-LOX in monocytes or epithelial cells and the 5-LOX in PMNs yielding an epoxide intermediate that is converted to LXA4 and LXB4 by leucocyte epoxide hydrolases. Third, aspirin acetylates the active site of COX2 (Asp-COX2) that now is able to metabolize AA to 15(R)-hydroxyeicosatetraenoic (15R-HETE), which when released from endothelial and epithelial cells is converted by leucocyte 5-LOX to the called aspirin-triggered LXs (AT-LXs), 15-epi-LXA4 and 15-epi-LXB4. Once AA is metabolized to AT-LXs, it is substituted by the ω-3 EPA and DHA as substrates of the E-series and D-series resolvins and protectins. Vascular endothelial Asp-COX2 converts EPA to 18R-hydroxyepoxy-EPE (18R-(p)EPE), which is further sequentially metabolized by leucocyte 5-LOX to lead the formation of resolving E1 (RvE1). Microbial P-450s may also convert EPA in RvE1. 5-LOX can also generate RvE2 from 18R-(p)EPE and further reduction. DHA is transformed by the leucocyte COX to 17S-(p)DHA, which is rapidly converted by PMN LOX into two epoxide intermediates that finally lead the formation of the bioactive products 17S-resolvin D series (RvD1 to RvD4). Alternatively, Asp-COX2 can metabolize DHA to a 17R-(p)DHA, which in turn generate the 17R-resolvin D series (AT-RvDs) by action of the leucocyte 5-LOX. Finally, by action of the 15-LOX in microglia, brain leucocytes, retinal cells or Th2 cells, DHA is converted to 17S-(p)DHA, which following further enzymatic epoxidation and hydrolysis form protectin 1 (PD1), or neuroprotectin 1 (NP1) if formed in the brain. LXA4, AT-LXs, resolvins and PD1 share some anti-inflammatory and pro-resolving actions, although they have distinct roles within the induction of resolution. dendritic cells, DC; inducible nitric oxide synthase, iNOS; peroxisome proliferator-activating receptor γ, PPARγ; transforming growth factor, TGF.
beneficial roles of the ω-3 PUFAs, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), in health and organ function were known from almost one century ago [133]. Both DHA and EPA are held to be beneficial in a wide range of human inflammatory diseases, including rheumatoid arthritis, Alzheimer’s disease, cardiovascular diseases, inflammatory bowel disease and lung fibrosis [134–139]. Until very recently, the established hypotheses about the mechanisms that govern these beneficial effects were that these ω-3 PUFAs prevent conversion of AA to pro-inflammatory eicosanoids (PGs and LTs) or serve as an alternative substrate generating less-potent products. However, the group led by C.N. Serhan dramatically changed the scenario in this field, since they uncovered a series of oxygenated derivatives of ω-3 PUFAs, named Resolvins (Rvs) and Protectins (PDs), which possess potent anti-inflammatory and pro-resolving actions [122, 140–147]. Thus, they found that EPA generates the 18R E-series resolvins (resolin E1 and resolin E2) in the presence of aspirin during the spontaneous resolution phase of acute inflammation where specific cell–cell interactions occur (Fig. 3). They also elucidated that DHA generates the 17S D-series resolvins (resolvin D1 to D6) and protectin D1 (PD1) through interaction with leucocyte LOX, and alternatively, DHA forms the 17R D-series resolvins (AT-RvDs) in the presence of aspirin-acetylated COX2 (Fig. 3).

RvE1 inhibits PMN transendothelial migration in vitro, reduces leucocyte infiltration in vivo, and inhibits DC migration and IL-12 production [140, 141, 147–150]. Moreover, RvE1 improved the survival of mice with colitis by reducing PMN recruitment and the expression of pro-inflammatory genes [151]. RvE1 can interact with the LTβR receptor (BLT1) in leucocytes and attenuate LTβR-stimulated signals, acting as a partial agonist or antagonist [152]. In addition, RvE1 seems to bind to the GPCR receptor ChemR23 and inhibit NFκB signalling through a mechanism that involves phosphorylation rather than mobilization of calcium or cAMP [152]. The other resolvins, especially RvD1, inhibit TNFα-induced IL-1β production by microglia, reduce PMN infiltration into inflamed brain, skin and peritoneum, and are protective in a model renal ischemic injury [141, 142, 153].

PD1, named as neuroprotectin D1 when produced in the neural tissue, also attenuates neutrophil transmigration in vitro and reduces in vivo PMN infiltration in models of peritonitis and cerebral stroke [142, 143]. Attending to its name, PD1 has shown neuroprotective effects, promotes corneal epithelial cell wound healing and repair, and protects from lung damage by reducing airway inflammation and from kidney injury [153–155]. PD1 is the only lipid mediator derived from ω-3 PUFAs that showed direct immunomodulatory effects on T-cell function. PD1 inhibits the production of IFNγ and TNFα by activated T cells and induces T cell apoptosis, suggesting that is down-regulating Th1-mediated responses [156]. Of note is the fact that PD1 is produced by Th2-skewed human peripheral blood mononuclear cells through a LOX-dependent mechanism [157]. This finding correlated with the early studies reporting that DHA modulates T-cell functions to favour a Th2 phenotype [157, 158], suggesting that PD1 is a major DHA conversion product that is biosynthesized during Th2 polarization and promotes anti-inflammatory responses.

On the other hand, RvE1, PD1 and LXA4 show an interesting mechanism to facilitate chemokine removal during resolution, consisting in the up-regulation of CCR5 expression on late apoptotic leucocytes, which sequester the CCR5 ligands and are then engulfed by resolving macrophages in a non-phlogistic manner [159]. Finally, an elegant and recent work has demonstrated that RvE1, PD1 and an ATL analogue promote inflammation resolution in a murine model of peritonitis, not only by reducing the recruitment (influx) of leucocytes to the inflammatory exudate (considered as anti-inflammation), but also promoting phagocyte removal (considered as pro-resolution) by stimulating macrophage ingestion of apoptotic neutrophils and microbial products and enhancing the efflux of these phagocytes from inflamed peritoneum to draining lymph nodes and spleen [160].

These findings outline the potential application of these lipid mediators in acute inflammatory diseases. However, their relevance in autoimmune disorders is still unknown, since research on the effect of lipid mediators in T-cell activity is scarce. This is probably an emerging field and further studies will determine whether we can extend their therapeutic use to autoimmune disorders. Similar to neuropeptides, the induction of immune tolerance by lipid mediators should be a critical point.

**Therapeutic perspectives: rationale for using endogeneous neuropeptides and lipid mediators in immune disorders**

Our body responds to an exacerbated inflammatory response by increasing the production of endogenous anti-inflammatory neuropeptides and lipid mediators, in an attempt to restore the immune homeostasis [161–167]. The findings reviewed above indicate that these neuropeptides act in a pleiotropic and in many cases in a redundant manner to regulate the balance between pro-inflammatory and anti-inflammatory factors, and between autoreactive Th1 cells and Treg cells. Lipid mediators such as LxS, Rvs and PDs each play an active role in controlling and programming resolution of inflammation and stimulating endogenous anti-inflammatory and pro-resolving pathways. Based in these characteristics, anti-inflammatory neuropeptides and pro-resolving lipid mediators could represent feasible therapeutic agents in the treatment on immune diseases, such as rheumatoid arthritis, multiple sclerosis or Crohn’s disease, characterized by a double component, inflammatory and autoimmune.

**Advantages of using endogeneous neuropeptides and lipids**

From a therapeutic point of view, the wide spectrum of action of these endogenous mediators represents an advantage versus agents directed only against one component of these diseases. In
addition, the promotion of an active program of inflammation resolution by lipid mediators is therapeutically attractive because the goal is restoration of tissue homeostasis without significantly affecting key components of the inflammatory response (i.e. cytokines). However, although both neuropeptides and lipids have revealed their clinical therapeutic possibilities, most studies were performed in animal models, and precautions should be taken to extend them to human diseases. This will depend on the dosage of these factors and expression of specific receptors in the different cell types participating in the immune response. In addition, we should also consider the potential side effects as a consequence of the other effects of these neuropeptides and lipid mediators in the body, such as hypotension, gut motility and endocrine disorders, reproductive activity, diarrhoea and circadian rhythm and memory alterations. It is important to note that some of these neuropeptides have been already tested in human beings for the treatment of sepsis and other disorders [168–171], without such complications. This suggests that they should be well tolerated in human beings in doses similar to those that are able to prevent immunological diseases in animals. Therefore, as compared to existing anti-inflammatory drugs, neuropeptides are not associated with dramatic side effects, because as physiological compounds they are intrinsically non-toxic. In addition, neuropeptides are rapidly cleared from the body through natural hepatic detoxification mechanisms and renal excretion. Moreover, other cytokines, neuropeptides and hormones often counterbalance their actions, meaning that the homeostasis of normal tissues should not be excessively perturbed. Regarding lipid mediators, lipoxins, PD1 and Rvs are rapidly generated in response to stimuli, act locally and then are rapidly inactivated by metabolic enzymes (i.e. LAX4/PGE 13, 14-reductase/LTB4 12-hydroxydehydrogenase). Therefore, no side effects should be expected for them.

In addition to their wide spectrum of action, the molecular structure and size of the neuropeptides and lipid mediators make them attractive compounds to treat excessive inflammation. As small molecules, they possess excellent permeability properties that permit rapid access to the site of inflammation. This is critical for neuroinflammatory disorders, where the blood-brain barrier is partially disturbed. The second advantage owes to their high-affinity binding to specific receptors, thus making them very potent in exerting their actions. Finally, the in vitro synthesis of neuropeptides and lipid mediators is straightforward and permits easy modification if necessary.

**Cell-based therapy**

An important aspect for translational medicine is the induction of Treg cells by neuropeptides. This has not only been crucial to a better understanding of the immunomodulatory action of neuropeptides, but has also supposed the proposal of a new cell-based strategy for the treatment of immune disorders where tolerance restoration is needed. Considerable effort is recently focused on the use of antigen-specific Treg cells generated ex vivo to treat autoimmune diseases, transplantation and asthmatic disorders [4]. The ability to translate important biological findings about Treg cells to the clinic has been limited by several issues, including the low frequency of these cells and the potential for pan immunosuppression. The potential solution for this problem should consist in expanding them and making them antigen-specific using selected antigens and peptides. However, although Treg cells replicate relatively efficiently in vitro, they are anergic and refractory to stimulation in vitro [4, 5]. Therefore, protocols that efficiently expand Treg populations in vitro while maintaining their immunoregulatory properties in vivo should be based on the conditions that allow their expansion in vivo, including TCR occupancy, crucial co-stimulatory signals and selective growth factors. Neuropeptides could be one of these endogenous growth factors involved in the generation/expansion of Treg cells. In fact, neuropeptides induce the generation of self-peptides-specific Treg cells from otherwise conventional T cells in vitro. These cells prevent very efficiently the progression of experimental autoimmune diseases by suppressing the systemic autoantigen-specific T and B-cell responses and the tissue-localized inflammatory response. On the other hand, the capacity of certain classes DCs to induce Treg cells makes them attractive for the expansion/generation of antigen-specific Treg cells ex vivo, or alternatively, for their use in vivo as therapeutic cells that restore immune tolerance by inducing Treg cells in the host [172, 173]. In this sense, VIP-induced tolerogenic DCs pulsed with self-antigens have been shown to ameliorate the progression of rheumatoid arthritis, EAE and inflammatory bowel disease [106, 174]. This effect is mainly mediated through the generation of antigen-specific Treg cells in the treated animal. Probably, the most important issue that the cell-based therapy with neuropeptide-induced Treg cells or tolerogenic DCs needs to resolve is to determine the necessity of antigen specificity. Whereas polyclonal Treg cells might function in allograft transplantation and autoimmunity in lymphopenic (i.e. systemic lupus eritematous) or inflammatory bowel disease settings, in other autoimmune disorders antigen-specific Treg cells are most effective [4]. In this sense, etiology and self-antigens in most human autoimmune disorders are mostly unknown, reducing the therapeutic efficiency and applicability of Treg cells. In addition, the proposed cell-based therapy will require an ex vivo manipulation of the blood cells of patients. Therefore, it is necessary to determine whether neuropeptides in vitro are able to generate Treg cells or tolerogenic DCs with the same efficiency, reliability, homing capacity and survival in vivo compared to those obtained from animals or healthy individuals, since in contrast to mouse models, in patients there exists considerable variability. In any case, what this is an individualized therapy, which will involve procedures that are likely to be expensive, but which will be indicated to patients that are non-responsive to established treatments.

**Pitfalls: how to solve them?**

Despite the potential advantages of using neuropeptides on immune disorders, several obstacles stand between translating
neuropeptide-based treatment into viable clinic therapies. Due to their natural structural conformation, neuropeptides are very unstable and extremely sensitive to peptidases present in most tissues. Several methodological strategies have been developed to increase the neuropeptide half-life, especially in long-term treatments. For example, modifications or substitutions of certain amino acids in the sequence or cycling the structure increase the stability of these peptides [175, 176]. Perhaps even more important is work towards improving neuropeptide delivery to target tissues and cells while protecting it against degradation. Different strategies being tested under experimental conditions include neuropeptide gene delivery or the insertion of VIP into micelles or nanoparticles [66, 71, 177–180]. Other methods include combining neuropeptide treatment with inhibitors of neutral endopeptidases to reduce the degradation of the peptide in the circulation. Alternatively, administration of serum-specific neuropeptide binding proteins (i.e., adrenomedullin binding protein-1) would protect them from peptidases and enhance their delivery in the proximity of their receptors in the inflamed tissue [96]. Other combinatory treatments aim to take advantage of the fact that activation of the cAMP/PKA pathway appears to be the major signal involved in their immunomodulatory effect. Thus, combining neuropeptides with inhibitors of phosphodiesterases (enzymes involved in the degradation of cAMP) has been found to be therapeutically attractive in the treatment of some inflammatory diseases [181–183].

However, the definitive approach by the pharmaceutical companies as a prerequisite for successful clinical applications is the development of metabolically stable analogues. Understanding of the structure/function relationship of these neuropeptides and their specific receptors, including receptor signalling, internalization and homo/heterodimerization, will facilitate the development of novel pharmacologic agents for translational medicine. However, in the case of the type 2 GPCRs (i.e., receptors for VIP, urocortin, αMSH and adrenomedullin), the pharmaceutical industry has so far failed to generate effective non-peptide-specific agonists [184]. Even where synthetic agonists were designed specifically for VIP receptors, they were less effective than the natural peptide as anti-inflammatory agents [25]. In the case of the type 1 GPCRs, the generation of several somatostatin agonists offered new therapeutic opportunities for the treatment of acromegaly and endocrine tumours [185]. However, compared to cortistatin, some somatostatin agonists (i.e., octreotide) show much less effectiveness, if any, reducing inflammation and autoimmunity [10, 11, 186]. It remains to be investigated whether recently isolated non-peptide ghrelin-receptor agonists share some therapeutic actions with ghrelin. Regarding pro-resolving lipid mediators, screening for non-LXA4 agonists of the LXA4 receptor ALX/FPRL-1 resulted in the identification of orally active anti-inflammatory agents in animal models [15, 186], although their efficiency in human diseases remains untested. In any case, the focus on the use of natural peptides in therapy is not new, and may be a case of history repeating itself, since naturally occurring human compounds have often proved to have striking therapeutic value (e.g., insulin and cortisone). Elucidation of the molecular mechanisms of the reported beneficial actions of ω-3 PUFA has supposed an important challenge for molecular and translational medicine.

Finally, it is important to take into account that many drugs currently used in inflammatory diseases were developed without an appreciation of their potential impact in resolution. Thus, the widely used COX-2 inhibitors have been proven to be resolution toxic, whereas other agents such as glucocorticoids or aspirin can possess pro-resolving actions [15]. Although neuropeptides inhibit the infiltration of leucocytes to the inflamed tissue, it is still unknown whether they are able to actively promote programs of inflammation resolution similarly to lipid mediators. However, two recent studies have reported that VIP and the structurally related pituitary adenylate cyclase-activating polypeptide (PACAP) bind to the ALX/FPRL-1 in monocytes [187, 188], suggesting that both neuropeptides could mimic LXA4-mediated resolving actions. In any case, combinatory treatment with both anti-inflammatory neuropeptides and pro-resolving lipid mediators emerges as an attractive therapy for many immune disorders that course with exacerbated inflammatory responses.

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