Title: Mechanisms of Action That Contribute to Efficacy of Omalizumab in Chronic Spontaneous Urticaria

Short Title: Omalizumab for Chronic Spontaneous Urticaria

Authors: Allen P. Kaplan, MD;¹ Ana M. Giménez-Arnau, MD, PhD;² Sarbjit Singh Saini, MD³

Affiliations: ¹Department of Medicine, Division of Pulmonary and Critical Care Medicine, Allergy and Clinical Immunology, Medical University of South Carolina, Charleston, SC, USA; ²Department of Dermatology, Hospital del Mar, Institut Mar D’Investigacions Mediques, Universitat Autònoma, Barcelona, Spain; ³Johns Hopkins Asthma and Allergy Center, Baltimore, MD, USA

Corresponding author and person from whom offprints are to be requested: Allen P. Kaplan, MD, Division of Pulmonary, Critical Care Medicine, Allergy and Clinical Immunology, Medical University of South Carolina, 1879 Savage Rd, Charleston, SC 29425. Phone: +1 (843) 722-1253; E-mail: kaplana@musc.edu

Emails: anamariagimenezarnau@gmail.com; ssaini@jhmi.edu
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Conflicts of Interest

Allen P. Kaplan is a consultant for Novartis/Genentech, he also adjudicates allergic reactions due to antihypertensive agents and drugs for diabetes for Novartis.

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ABSTRACT

The monoclonal anti-immunoglobulin E (IgE) antibody, omalizumab, was the first drug approved for use in patients with chronic idiopathic/spontaneous urticaria (CIU/CSU) who remain symptomatic despite H1-antihistamine treatment. Omalizumab binds to free IgE, which lowers free IgE levels and causes FcεRI receptors on basophils and mast cells to be downregulated. It has been shown to improve symptoms of CIU/CSU, but its mechanism of action is not currently understood. Potential mechanisms in CIU/CSU include reducing mast cell releasability, reversing basopenia and improving basophil IgE receptor function, reducing activity of IgG autoantibodies against FcεRI and IgE, reducing activity of IgE autoantibodies against an antigen or autoantigen that has yet to be definitively identified, reducing the activity of intrinsically “abnormal” IgE, and decreasing in vitro coagulation abnormalities associated with disease activity. However, none of these theories alone or in combination fully account for the pattern of symptom improvement seen with omalizumab therapy, and therefore, no one mechanism is likely to be the definitive mechanism of action. Additional research is needed to further clarify the involvement of omalizumab in relieving symptoms associated with the complex, multifactorial pathogenesis of CIU/CSU.
Introduction

Chronic idiopathic/spontaneous urticaria (CIU/CSU) is characterized by itching, burning or painful evanescent wheals (hives) and/or angioedema, symptoms that present suddenly and are present most days of the week for at least 6 weeks (1, 2). Inducible urticarias can also be chronic, but can be provoked by physical stimuli (e.g., cold, friction, or pressure) or other factors (e.g., in cholinergic, aquagenic, or contact urticaria) (1, 2). With the exception of delayed pressure urticaria, the individual urticarial lesions in inducible urticarias appear shortly after provocation and usually fade within 4 hours (typically 1–2 hours) (1) whereas the typical lesions in CIU/CSU may persist for longer periods of time (3). The extended duration of lesions in CIU/CSU and delayed pressure urticaria may be attributed to a late-phase response similar to allergic reactions in which a lesion appears 4 to 10 hours after a preceding immediate hive has disappeared (1, 4-8).

The prevalence of CIU/CSU is difficult to estimate as few studies have focused on it, and inconsistent classification of urticaria makes it difficult to compare individual studies (9). Up to 1.0% of the global population may suffer from CIU/CSU at any given time (9). In a retrospective study of insurance claims from a US commercial health plan, the prevalence of CIU/CSU was found to be 0.11% (10).

The wheals in patients with CIU/CSU are superficial swellings of the dermis that usually begin as skin lesions with red edges and a pale center, becoming pink as they mature (11). The pathology of active wheals shows degranulated mast cells and a dermal infiltrate with a variable number of lymphocytes, eosinophils, neutrophils, basophils, or macrophages (7, 12-14). Mediators such as histamine, platelet-activating factor, prostaglandin D2, and cytokines released from mast cells and endothelial cells contribute to the vasodilation, nerve activation, and cell recruitment seen in the wheals (15-20). Upregulation of endothelial cell adhesion molecules is typically present in skin affected by wheals, and preliminary findings suggest that patients with CIU/CSU show upregulation of genes involved in the recovery of the epidermal barrier, active inflammation, coagulation, and dermal repair (21-23).

Mast cells, the principal cells involved in wheal pathogenesis, express multiple receptors that are susceptible to activation, inducing their degranulation (e.g., chemokine, prostaglandin, Toll-like, or immunoglobulin receptors) (17, 24, 25). A key receptor in CIU/CSU is the immunoglobulin E (IgE) receptor FceRI (26-28), although there is some evidence that it is not always involved in mast cell activation and histamine release (29), and multiple pathways leading to mast cell activation have been identified (30).

Here we review clinical data showing the pattern of symptoms and changes in biomarkers as well as data from in vitro studies that provide new insights into the potential mechanisms of
action contributing to the efficacy of omalizumab, an anti-IgE antibody, in CIU/CSU. Previous reviews have focused on the utility of omalizumab as treatment for CIU/CSU and potential mechanisms of action, with an emphasis on mast-cell priming via monomeric IgE and autoreactivity (31, 32). The current review expands on these and presents potential mechanisms related to the modulation of basophil IgE receptor function, evidence for activation of coagulation factors, and possible mechanisms involving autoantigens or “abnormal” IgE. We also present newly available data showing that omalizumab reduces FceRI and IgE and normalizes gene expression in patients with CIU/CSU.

Omalizumab overview

Omalizumab for treatment of patients with CIU/CSU

Omalizumab is a recombinant DNA-derived humanized immunoglobulin G1κ monoclonal antibody that selectively binds to human IgE (33). It was originally approved in the USA in 2003 for the treatment of moderate-to-severe persistent allergic asthma and then in the European Union (EU) in 2005 for treatment-resistant allergic asthma (33, 34).

Omalizumab was approved for use in patients with CIU/CSU in 2014 in both the USA and EU (33, 35, 36) and three phase 3 studies have confirmed it is efficacious in this population (37-39). It is the first drug approved for patients with CIU/CSU who remain symptomatic despite H1-antihistamine treatment (1, 2, 31, 35).

The reduction of inflammatory mediator release by omalizumab in patients with allergic disease requires a 95% reduction in serum IgE levels to modify allergen responses via receptor downregulation (40, 41). Thus, dosing for allergic asthma is determined by serum total IgE level and body weight to achieve this reduction in IgE (33). By contrast, CIU/CSU is not a classic allergen-driven disease and a fixed dose of omalizumab is approved for use in patients with CIU/CSU (37-39, 42). The mechanism of action that results in improvement of CIU/CSU symptoms is not entirely understood (32).

Known mechanism for omalizumab in allergic diseases

Omalizumab was developed to bind with high affinity to free IgE, thereby preventing allergen-specific IgE from attaching to FceRI (40, 43). Omalizumab does not bind to cell surface IgE so it does not directly activate mast cells or basophils (44, 45). The reduction in free IgE levels results in reduction of the number of FceRI receptors on mast cells, basophils, and antigen-presenting cells (40, 41, 43, 46-48). Several studies have shown that a residual response to allergen triggering of mast cells and basophils remains, albeit with reduced mediator generation (40, 49).
The rate of change to suppress IgE, IgE receptors, and allergen responses varies by cell type (Figure 1A, based on asthma dosing strategy studies) (40, 43, 50-54). Significant reduction in basophil FcεRI was noted as early as 3 days following the first dose of omalizumab in patients with allergic disease (40, 51). In patients with allergic rhinitis, FcεRI on basophils decreased by 88% at Day 7 but did not decrease on mast cells until Day 70, at which point acute allergen wheal size decreased (43). Clinical response to omalizumab in patients with peanut allergy was observed before Week 8, a time-frame during which basophils, but not skin mast cells, were found to be suppressed in their allergen responses (52). Likewise, reductions in cat allergen nasal reactivity with omalizumab therapy occurred in an early time-frame, before notable reductions in the size of the early-phase skin reaction or nasal mast cell mediator production (51, 53, 54).

In these allergen challenge models and often patients with CIU/CSU, omalizumab treatment led to symptom relief well before a reduction was seen in the size of the early-phase reaction of patients with allergic disease (37-39, 42, 55-58). Conversely, the late-phase reaction of allergen-induced responses resembles that seen in CIU/CSU (7). Also, acute administration of corticosteroids affects only the late-phase response of CIU/CSU (59) and has no effect upon allergen-induced mast cell degranulation. For example, one can administer skin tests to patients who are on steroid therapy. During antigen challenge in patients with allergic disease, omalizumab has a faster and greater effect on the skin late-phase than the early-phase response, and may act on infiltrating cells in addition to resident mast cells (53, 54). Thus, it is important to note that the insights gained from the effects of omalizumab on allergic reactions, particularly the responsiveness of mature skin mast cells, may not directly apply to CIU/CSU.

Rationale for evaluating omalizumab for CIU/CSU

It was theorized that omalizumab could prevent activation of mast cells and basophils in the approximately 40–45% of patients with CIU/CSU who may have an autoimmune component, by decreasing FcεRI density and preventing immunoglobulin G (IgG) antibody-mediated cross-linking of adjacent α-subunits or IgE itself (60). Further, there is evidence that patients with CIU/CSU have an abnormal basophil FcεRI pathway and that basophils are recruited to CIU/CSU lesions (26, 55, 61-63). Reversal of basopenia and basophil IgE receptor abnormalities, seen in natural remission of CIU/CSU, points toward basophils as an important contributor to disease (62, 64, 65). Omalizumab might target the uniquely abnormal basophil FcεRI phenotype and recruitment to the skin, as seen in patients with CIU/CSU.

An initial case report in 2007 showed that three patients receiving omalizumab for the treatment of asthma also had symptomatic chronic (CU) that responded to treatment with omalizumab (66). A proof-of-concept study of omalizumab in patients with autoimmune-related CU,
demonstrated by basophil studies or autologous skin testing, suggested that omalizumab may be an effective therapy in patients who are not adequately treated with antihistamines (60) and a second proof-of-concept study evaluated patients regardless of autoimmune status with similar success (55). These led to a phase 2 dose-ranging study that found omalizumab was well-tolerated and efficacious (42), and phase 3 studies of more than 900 patients led to approval of omalizumab’s CIU/CSU indication (37-39).

**Potential mechanisms of action in CIU/CSU**

**Lowering IgE levels and downregulating IgE receptors**

The ability of omalizumab to lower free IgE levels and downregulate FcεRI on mast cells and basophils is well established (40, 43, 49, 67). The reduction in FcεRI levels is the result of unbound FcεRI being degraded when they are not stabilized by binding to IgE (40, 41, 47, 48, 68).

A recent randomized controlled study found that baseline levels of FcεRI- and IgE-positive cells were higher in patients with CIU/CSU than in healthy volunteers, but after 12 weeks of omalizumab treatment levels in lesional and non-lesional skin were reduced to levels seen in healthy volunteers (57). Although the effect of omalizumab is clear, the baseline level of FcεRI- and IgE-positive cells in CIU/CSU may reflect the observation that IgE levels in the CIU/CSU group were 50% higher at baseline compared with the unmatched controls (69). Omalizumab treatment also altered the expression of genes associated with mast cell/leukocyte infiltration (FECER1G, C3AR1, CD93, S100A8, S100A9), increased oxidative stress (SOD2), vascularization (CYR61) and skin repair events (KRT6, KRT16A) in lesional skin to the levels seen in non-lesional skin and skin in healthy volunteers, as measured by microarray (70). Pooled data from all phase 3 studies showed that symptom reduction in CIU measured by 7-day sum of daily Urticaria Activity Scores (UAS7) was correlated with a reduction in free IgE levels relative to baseline using data collected at 12 and 24 weeks of omalizumab treatment (71). In patients with allergic disease, this combination of lowered IgE and FcεRI levels reduces allergen-stimulated responses of mast cells and basophils (43), despite an increase in the intrinsic sensitivity to allergen stimulation for basophils (49). How this relates to cell secretion in CIU/CSU, in which the agonist is not as well defined, is not yet clear.

It is of note that omalizumab therapy is successful in patients with or without a positive test for IgG autoantibodies against FcεRI or IgE, or IgE autoantibodies against thyroperoxidase (37-39, 42, 55, 60, 72). In one phase 3 study, omalizumab therapy had a similar response in patients regardless of CU index status (39). Although a 24-hour time point was not evaluated in phase 3 studies, a retrospective study reported that within 24 hours >50% of patients experienced symptom control, defined as a reduction of ≥90% of UAS7 (58), suggesting that in some patients
symptom control may be achieved too quickly to be explained by IgE receptor downregulation (Figure 1B) (40, 43, 73). Numerous studies have noted this rapidly responding subpopulation but report a much smaller percentage within the first week (37-39, 74, 75). Regardless, several additional theories need to be explored.

**Reducing mast cell releasability**

Cutaneous mast cells appear to have unique characteristics compared with mast cells in other locations (77, 78). For example, human cutaneous mast cells degranulate in response to opiates and substance P, and have complement receptors, unlike pulmonary mast cells, which do not (78, 79). Mast cell releasability, as assessed by compound 48/80-induced histamine responses via skin chambers, has been demonstrated to be increased in patients with CIU/CSU as compared with healthy controls (Jacques et al. 1992, Bedard et al. 1986, Brunet et al. 1990); this enhanced releasability has been shown to reverse with CIU/CSU remission (Jacques et al. 1992). Furthermore, levels of Mas-related gene X2 (MrgX2), a receptor expressed on human mast cells for basic proteins including compound 48/80 (Tatemoto et al. 2006), is known to increase in the skin of patients with CIU/CSU (Fujisawa et al. 2014). Separately, it has been noted that CD34+ derived mast cells of subjects with CIU have enhanced spontaneous release (Saini et al. 2010).

In skin biopsies from patients with allergic rhinitis, omalizumab reduced the number of available FcεRI receptors much more slowly on mast cells than on basophils (70 vs 7 days) (43). This difference in effect on mast cells versus basophils may be attributable to the relatively brief transit time of basophils in the circulation compared with the lifespan of tissue mast cells (80). The rate of receptor downregulation in skin mast cells of patients with CIU/CSU is less clear but appears to support the earlier findings in subjects with allergic disease for rate of receptor reductions (43, 54). Recent skin biopsy data in patients with CIU/CSU treated with fixed dose omalizumab did not show significant IgE-/FcεRI-positive cell reductions until Day 85, yet symptoms were reduced by Day 8 (57). Many patients experienced a major clinical effect of omalizumab in the phase 3 studies within 2 weeks (37-39), thus some other mechanism must contribute to omalizumab’s earlier effects. In the phase 3 studies, 70–77% of responders (UAS7 ≤6) appear to do so at 4 weeks. This clinical effect was seen in 36–51% of patients at Week 4 and 52–66% at Week 12, (74) the latter within the time-frame of receptor downregulation. Studies of mast cell activation or releasability as mechanisms of omalizumab action are needed.

Evidence that further supports the theory that omalizumab can act to change mast cell releasability includes reports that omalizumab improves symptoms in patients with disorders
of mast cells (81, 82). The response of two patients was slow, consistent with what is known about the time required for omalizumab to reduce receptors on mast cells compared with basophils (Figure 1A) (82). Furthermore, a retrospective analysis of omalizumab therapy found several patients with cold urticaria and dermatographism had a complete response (58), yet these conditions do not include a late-phase response or a known role for basophils.

**Reversing basopenia and improving basophil IgE receptor function**

Evidence that shows basophils play a role in CIU/CSU pathogenesis includes findings that patients with CIU/CSU have basopenia, based on manual and flow cytometry basophil counts and histamine content in blood, which are not routine clinical procedures (61, 83-86). In clinical practice, basopenia can be evaluated by complete blood count (87).

Two observational studies of adult patients with active CIU/CSU found an inverse relationship between the number of basophils and disease severity (65, 83). In two observational studies of patients with CIU/CSU who had recurrent hives for more than 3 months, staining with BB1, a novel monoclonal antibody that recognizes basogranulin, identified that basophils are present in biopsies of non-lesional and lesional skin (7, 88). A recent study confirmed the role of basophil infiltration in CSU and demonstrates that there are slightly higher numbers of basophils in lesional compared with non-lesional skin (89). These findings suggest basopenia may reflect the recruitment of basophils to skin tissue; however, the recruitment pathways for this migration have not been identified (65, 90, 91). An evaluation of basophil infiltration in 24 skin diseases found that basophil accumulation in the skin and basophil activation in the bloodstream are relatively unique to CIU/CSU (12).

Treatment with omalizumab has been shown to increase basophil IgE receptor sensitivity to allergen-driven secretion in patients with allergic airways disease and peanut allergy (49, 92, 93). However, this finding does not directly relate to the mechanism of omalizumab in CIU/CSU because the baseline state of basophils is abnormal in CIU/CSU (26).

Several studies have found that basophils in patients with CIU/CSU released less histamine than healthy control subjects when they were tested with anti-IgE or anti-FcεRI antibodies, but not when exposed to agents that act independent of the FcεRI pathway (62, 63, 85, 90, 94, 95). This suggests that a selective defect in the FcεRI signaling pathway of basophils is likely in patients with CIU/CSU (62, 63, 85, 94, 95). An observational study seeking to identify the mechanism associated with this altered histamine release characterized two functional basophil phenotypes that have been identified among patients with CIU/CSU in approximately equal numbers: those who have normal histamine release (responders) and those who release significantly less histamine (non-responders) (94). The abnormal responsiveness appears to be due to elevated expression of intracellular phosphatases, which dephosphorylate molecules
essential for histamine release (94). In an observational study of 64 patients with CIU/CSU separated by functional basophil phenotypes based on their degree of histamine release, levels of IgG autoantibodies against FcεRI and IgE and functional basophil phenotype remained stable in those with active disease. IgG anti-FcεRI and anti-IgE autoantibody titers did not correspond to basophil functional phenotype and when basophil IgE receptor function improved in patients who went into remission, no changes in the autoantibody titers were noted (64). A recent study showed that basophils of healthy donors cultured in serum from patients with active CIU/CSU displayed suppression of IgE receptor activation. The suppressive capacity of active CIU/CSU patient serum persisted after IgG or IgE depletion, but was not observed in cultures using serum from patients with CIU/CSU in remission (96). This suggests that active CIU/CSU skin disease may impart a suppressive factor in serum that suppresses basophil IgE function.

Additionally, phase 3 study participants at US sites had whole blood samples monitored for histamine content, an indirect measure of number of basophils. Overall increases in whole blood histamine content were noted in participants treated with omalizumab compared with placebo ((97), manuscript in preparation). Parallel clinical improvement assessed using the itch severity score supports the concept that improvement of basopenia in active CIU/CSU is associated with reduced clinical symptoms, suggesting again that basophil recruitment to the skin is related to CIU/CSU symptom expression and a pathway that is altered by omalizumab (97).

A recent study comparing omalizumab treatment with placebo in patients with CIU/CSU found that mean peripheral blood basophil counts increased as early as the first 8 days and continued to Day 85 of treatment in patients taking omalizumab (69). Similarly, mean IgE bound tobasophils and FcεRI expression on basophils were noticeably reduced by Day 8, remaining suppressed throughout the omalizumab treatment period (57, 69). Interestingly, the timing for the changes in blood basophils aligned with the onset of symptom relief seen on Day 8 of omalizumab treatment, which is earlier than when major changes to skin IgE receptors have been seen in skin biopsies (Figure 1B) (57, 69). In a separate study with omalizumab in patients with CIU/CSU, Gober et al. found that this therapeutic antibody improved basophil IgE-receptor-mediated histamine release (55). While evidence supports a role for basophils in CIU/CSU, the exact origin of the basophil abnormalities in this disease is under active study. Whether these basophil abnormalities are pathogenic in the subpopulation in whom they are evident or are a consequence of having CIU/CSU is unclear. Regardless, omalizumab may reverse a mechanism that recruits basophils to the skin and suppresses their IgE receptor pathway.

Reducing activity of IgG autoantibodies against FcεRI and IgE
The approved fixed dose of omalizumab for use in patients with CIU/CSU reflects that CIU/CSU is not a classic allergen-driven disease (37-39, 42). However, it is a long-held theory that IgG autoantibodies against FcεRI and/or IgE could play a role in approximately 40–45% of patients with CU (16, 28, 98-102). In the most common situation (35–40%), an IgG autoantibody directed to the α-subunit of FcεRI causes α-subunits to cross-link and leads to in vitro histamine release from basophils and mast-cell degranulation in some patients (28, 60, 100). A smaller fraction of patients with CU (5–10%) has functional IgG anti-IgE autoantibodies that release histamine from basophils (101).

The presence of autoantibodies against thyroid antigens (discussed below), FcεRI and IgE in patients with CIU/CSU suggests that CIU/CSU is associated with autoimmunity or that there is an autoimmune subset of CIU/CSU in which autoantibodies might contribute to pathogenesis (103, 104). Omalizumab could theoretically remove the effect of the autoimmune antigen by lowering the level of available surface IgE or IgE receptors. In support of this theory, levels of FcεRI- and IgE-positive skin cells in patients with CIU/CSU decreased in lesional and non-lesional skin following treatment with omalizumab (69). However, the timing of this decrease was not seen within the timeframe of the onset of symptom relief at Day 8 of treatment. Clinical efficacy was statistically significant at Week 2, but notable cellular effects were not statistically significant until Day 85 (Figure 1B) (69). Additionally, grouped data from three phase 3 studies showed that 1 week after starting omalizumab a partial response was experienced by approximately 10% of patients, and after 2 weeks roughly 30% and 15% of patients had a partial and complete response, respectively (74), which is earlier than changes occur in receptorfunctional responsiveness of cutaneous mast cells. As noted earlier, omalizumab therapy is successful in patients with or without a positive CU index test for autoantibodies against IgE, FcεRI, and FcεRII (37-39, 42, 55, 72). Also, titers of IgG autoantibody to IgE and FcεRI remain stable as patients enter natural remission (64).

Autoimmunity cannot explain why the drug works in patients with CIU/CSU who lack IgE-anti-thyroidperoxidase (TPO) autoantibodies and IgG autoantibodies to IgE and FcεRI (72) or why anti-TPO, anti-IgE, and anti- FcεRI autoantibodies can be present in patients with other conditions in the absence of urticaria or in healthy controls (105-107). Yet we know that with age, abnormal, disease-associated autoantibodies (antinuclear antibodies, rheumatoid factor) increase in healthy individuals with no corresponding clinical manifestations (108, 109). Further, autoimmune phenomena in rheumatoid arthritis (anticyclic antibodies) or systemic lupus erythematosus (SLE; anti-dsDNA) are rarely affected by therapies that control symptoms (110). Related issues are disparate reports of the incidence of anti-FcεRI in non-urticarial patients and disagreement regarding methods utilized (immunoblot, binding assays, ELISA, autologous skin test, or basophil histamine release). For example, one study reported positives
by ELISA in 0/41 healthy controls, 3/15 patients with SLE, 16/45 with dermatomyositis, and 106/281 with CU (111). A histamine release assay was performed on a fraction of those in each category, but the only positives were in those with CU, suggesting that the histamine release assay is more specific for CU (111). In keeping with these findings, positive histamine release assays were reported in 54/104 patients with CU and 0/35 patients with non-urticarial allergies seen consecutively in a clinical practice (112). In contrast, a report that demonstrated significant positive basophil histamine release assays in non-CIU/CSU controls (5/22) suggested that a positive histamine release cannot reliably point to CIU/CSU (107), while a separate study found positives by histamine release assay in 3/20 normal controls, 6/26 patients with SLE, and 9/27 with CU (105). Thus, specificity and pathogenicity of these antibodies is not clear even though they are strongly associated with CIU/CSU, and are functional.

Reducing activity of IgE autoantibodies against an unknown autoantigen

Elevated levels of IgE autoantibodies against TPO are present in 54% of patients with CIU/CSU (104). While it is unclear whether the 2-fold difference observed between patients with CIU/CSU and controls is clinically relevant, there is a clear association between CIU/CSU and autoimmune thyroid dysfunction (113-115).

Although there is no direct evidence of the tissue presence of TPO antigens in CIU/CSU, omalizumab could lead to a reduction of the levels of these IgE autoantibodies and/or a decrease of IgE receptor density on mast cells, thus inhibiting mast-cell activation (42, 56). Omalizumab therapy is successful in patients who have not been tested for the presence of IgE anti-TPO as well as those who are anti-TPO positive (38, 42, 56).

Studies are needed to evaluate TPO antigen presence in skin, IgE-anti-TPO as an inducer of mast cell degranulation, and the use of omalizumab in patients with CIU/CSU and no IgE-anti-TPO autoantibodies (56). The incidence of IgE anti-TPO in patients with Hashimoto’s thyroiditis and no urticaria is not known, although they must have IgG-anti-TPO or IgG antithyroglobulin. Presently, higher levels of IgE-anti-TPO were identified in patients with CU than in a healthy population, but the pathological significance for the majority of patients with CIU/CSU needs further characterization (104).

Reducing activity of intrinsically “abnormal” IgE

“Abnormal” IgE may contribute to symptoms in a subset of patients with cold-induced urticaria (102). Passive-transfer experiments found that symptoms of urticaria could be induced in healthy patients by injecting them with serum from patients with cold-induced urticaria (116, 117). Further studies found that in some cases, the serum factors that initiated symptoms were associated with IgE (118-120).
The involvement of an IgE cryoglobulin has been disproven and the association of a cold-inducible antigen in skin has not yet been demonstrated; therefore, transfer of an intrinsically “abnormal” IgE has been suggested as the potential mechanism (121). Additionally, experiments using reverse passive transfer, in which the serum was injected after healthy skin was exposed to the stimulus that induces urticaria symptoms, failed to produce symptoms, suggesting a cold-induced conformational change in bound IgE is needed (116). The potential of such an intrinsically “abnormal” IgE as a component of the pathogenesis of CIU/CSU is then supported by findings that omalizumab was effective in treating a patient with cold-induced urticaria (122). Complete responses have also since been reported in 3/6 patients with cold urticaria and 6/7 with dermatographism (58). These disorders have in common rapid mast cell secretion of histamine, no cellular infiltrate, and reports of successful passive transfer due to IgE.

Similar to the theory that omalizumab reduces the activity of IgE autoantibodies, omalizumab may help to reduce the opportunity for “abnormal” IgE to stimulate mast cells and basophils. Recent ex vivo observations that a high concentration of omalizumab catalyzes rapid dissociation of bound IgE from human basophils isolated from patients with allergic disease could explain rapid responses to omalizumab in patients with CIU/CSU if the IgE were an autoantibody to any endogenous antigen or if the antibody was in fact causing or catalyzing cutaneous mast cell secretion. However, whether these findings are physiologically relevant in the clinical setting, where concentrations of omalizumab used are lower, is unknown (123). It has also been proposed that a combination of signals—not just IgE—are required to activate mast cells in patients with urticaria (116). A study of cultured mast cells showed that the mast cells of patients with CIU/CSU also spontaneously released histamine upon sensitization with normal IgE, suggesting that the initiation of CIU/CSU may require more than one component (27).

**Decreasing the role of coagulation involvement**

Because of the tight interplay between coagulation and inflammation, coagulation may play a role in the pathology of CU (124-131), and thus may be relevant to CIU/CSU. A series of studies have found that increased levels of prothrombin cleavage fragments resulting from an activated extrinsic coagulation pathway may play a role in the pathogenesis of CU. Plasma markers of thrombin generation were elevated in patients with active CU, and these markers decrease during remission (125-128). Accelerated thrombin generation might activate mast cells and increase the permeability of skin (132, 133).

In patients with CU, eosinophils are the main cells expressing tissue factor (134), which activates the coagulation cascade that leads to thrombin formation (127). In skin lesions of
patients with CU, tissue factor was strongly expressed by upper dermal inflammatory cells, with increased immunoreactivity compared with normal controls (127). Furthermore, association of disease severity with the activation of the coagulation pathway was observed (127). Eosinophils can be activated by IgG autoantibodies against FcεRII/CD23 that are found in some patients with CIU/CSU (135). However, the activation might be secondary to the activation of mast cells by FcεRI and IgE autoantibodies or unknown factors (128). It is proposed that eosinophils may play a role in CIU/CSU pathology only in patients who have IgG antibodies against FcεRII (whose incidence is unknown) but not against FcεRI and IgE (136).

In studies using rodent mast cells, thrombin has been shown to induce mast cell degranulation (133, 137). However, there are no human studies showing that thrombin induces mast cell degranulation (136) and “active” thrombosis has never been demonstrated to be present in CIU/CSU (124). A confounding observation is that the same abnormality in markers of thrombin formation are present in hereditary angioedema types I and II, for which the pathogenesis is clear (138, 139), and there is no clinical thrombosis. Here, coagulation abnormalities could reflect endothelial cell activation related to bradykinin formation, suggesting abnormalities that reflect increased vascular permeability regardless of cause.

Summary

Although it is clear that omalizumab is an effective treatment for many patients with CIU/CSU, the mechanism of action remains elusive. Much has been learned to date, yet no current theories, alone or in combination, can explain all aspects of the mechanisms that underlie the efficacy of omalizumab for patients with CIU/CSU (Table 1). Known mechanisms of mast cell activation or releasability, or downregulation of IgE receptors do not explain all the effects of omalizumab. The reversal of basopenia and improvement of basophil IgE receptor function observed with use of omalizumab do not explain the effect on mast cells and other cells involved in CIU/CSU lesions. Furthermore, the incidence of IgG autoantibodies against FcεRI and IgE and IgE autoantibodies against an antigen or autoantigen that has yet to be definitively identified does not exceed 50% and the extent of overlap with those who have basophil abnormalities is not known. The rate of symptom relief does not align with the rate of omalizumab’s effect on mast cell receptors affected by IgG autoantibodies. Potential reduction of intrinsically “abnormal” IgE has been considered, but symptoms of CIU/CSU may require more than one initiating component. Finally, much is yet to be learned about the potential role of coagulation involvement in CIU/CSU.

Given that subsets of patients with CIU/CSU may have different disease mechanisms that are not yet fully understood, the challenge of finding evidence for more than one mechanism is great. Additional research is needed to further explore each of these potential explanations for
the mechanism of omalizumab (e.g. the role of mast cells versus basophils, cell reactivity, autoantibodies, and potential unknown serum factors) and the likely interplay among the theories.

Additional areas for future study may include the ability of omalizumab to inhibit the release of inflammatory cytokines, chemokines, and common mediators involved in wheal pathogenesis from cutaneous mast cells, basophils, and the vasculature. When antihistamine- and leukotriene-resistant patients are studied, approximately 40% have a complete response to omalizumab (i.e. no urticaria) with a total response rate of approximately 50–70% after 12 weeks. A small fraction respond extraordinarily quickly (i.e. within a few days) while the remainder improve more gradually, within 2–10 weeks (37-39). Thus, unique mechanisms may be relevant for subpopulations of patients with CIU/CSU, and studies providing definitive evidence about omalizumab’s mechanism of action should help define the underlying pathogenesis of this vexing disorder.
Figure 1. Time course of known cellular and clinical effects of omalizumab identified in studies focused on (A) patients with allergic response, mast cell diseases and (B) chronic urticaria

*MacGlashan et al. 2013 observed a 2.5- to 125-fold increase in basophil sensitivity after omalizumab treatment with sensitivity shifts noted at the midpoint and after 12 weeks of treatment

Table 1. Summary of Potential Mechanisms
References

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