IL-17 and infections

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Abstract  IL-17 immunity has been shown to be essential for mucocutaneous protection against \textit{Candida albicans} in mice and humans. However, mice with defective IL-17 immunity display broader susceptibility, as they are also prone to infections with diverse infectious agents at various sites. Humans with genetic defects affecting their IL-17 immunity usually suffer from chronic mucocutaneous candidiasis (CMC): recurrent or persistent infections of the skin, nails, and mucosae with \textit{C. albicans}, with or without other clinical signs. Most patients with autosomal dominant (AD) hyper-IgE syndrome (HIES) due to STAT3 deficiency or AD STAT1 gain-of-function display impaired IL-17-producing T-cell development, and CMC is one of their principal clinical manifestations. Similarly, patients with autosomal recessive (AR) autoimmune polyendocrine syndrome type 1 (APS-1) caused by AIRE deficiency have high levels of neutralizing autoantibodies against IL-17A, IL-17F and/or IL-22 and present CMC as their only infectious disease. Finally, CMC is the main clinical phenotype observed in patients with inborn errors specifically affecting IL-17 immunity. Indeed, patients with AD IL-17F deficiency or AR IL-17RA or ACT1 deficiency display CMC and, to a lesser extent, superficial staphylococcal diseases. \textit{Candida} infection was recently reported in psoriasis patients treated with anti-IL-17A antibodies. Careful monitoring for CMC is thus important during anti-IL-17 treatment.

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KEYWORDS
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Introduction

In both mice and humans, the IL-17 family of cytokines contains six members: IL-17A through IL-17F. The receptors for these cytokines belong to the IL-17R family, which has five members: IL-17RA through IL-17RE. In mice, IL-17A and IL-17F induce the secretion of antimicrobial peptides by epithelial cells and of factors activating and recruiting granulocytes, thereby contributing to the destruction and eradication of invading pathogens. Mice lacking the genes encoding IL-17A or IL-17RA are susceptible to a broad range of infections with bacterial, fungal, parasitic or viral pathogens, at various mucosal surfaces. They are also susceptible to disseminated infections with certain pathogens, such as Candida albicans and Listeria monocytogenes. In recent years, patients with impaired or abolished IL-17 immunity have been shown to be susceptible to chronic mucocutaneous candidiasis (CMC). We review here current knowledge about the role of IL-17 cytokines in host defense in mice and humans.

IL-17 immunity

Studies of both mice and humans lacking proteins involved in IL-17 signaling have helped to clarify the role of IL-17 in immunity. Loss-of-function mutations of IL17F, IL17RA, and ACT1, and gain-of-function mutations of STAT3 have been identified as genetic etiologies of CMC in humans. IL-17F belongs to the IL-17 family and IL17RA belongs to the IL-17R family. IL-17F and IL-17A bind, as homodimers (IL-17F/IL-17F and IL-17A/IL-17A) or heterodimers (IL-17F/IL-17A) to their receptor, which consists of the IL-17RA and IL-17RC chains. IL-17RA and IL-17RC have been shown to be essential for signaling downstream from IL-17A, IL-17F, and IL-17A/F, in both mice and humans. Indeed, fibroblasts from IL17RA−/− or IL17RC−/− deficient mice display no induction of IL-6 and KC/CXCL1 upon stimulation with IL-17A, IL-17A/F, and IL-17F. Similarly, fibroblasts from IL-17RA deficient patients do not respond to IL-17A and IL-17F homo- and heterodimers in terms of IL-6 and GRO-α production. Moreover, following its heterodimerization with IL-17RB, IL-17RA has been shown to be involved in the IL-25/IL-17E signaling pathway in mice.

Impaired or abolished IL-17 immunity and superficial C. albicans infections

Mouse models

Wild-type adult mice are naturally resistant to oropharyngeal colonization and disease caused by C. albicans. Complete clearance of C. albicans is observed within three to four days of oral inoculation, with no evidence of oral mucosal plaque formation. However, a number of knockout mouse models and mice into which neutralizing antibodies have been injected have been tested for oropharyngeal candidiasis (OPC). Mice lacking IL17A have been shown to be susceptible to cutaneous C. albicans infections. Mice lacking IL17A have been shown to be susceptible to cutaneous C. albicans infection. In addition, mice treated with antibodies directed against IL-17A and IL-17F have been shown to be susceptible to OPC. However, mice treated with anti-IL17A or anti-IL-17F Abs alone seem to be less susceptible to OPC than mice treated with a combination of these two antibodies, with anti-IL-17A antibodies being slightly more efficient than anti-IL-17F. Mice lacking IL17RA, IL17RC or ACT1 have much larger fungal loads in the oral cavity during
OPC than wild-type mice. In addition, a number of mice lacking proteins involved in IL-17 T-cell development have been shown to be susceptible to OPC. In particular, mice lacking the retinoic acid-related orphan receptor (ROR)-γt, a transcription factor inducing the production of IL-17 and IL-22, and possibly of other cytokines, have been shown to be susceptible to OPC. 38 By contrast, despite the prior demonstration that IL-1 and IL-6 are important for Th17 cell differentiation in mice, mice lacking IL-1R or IL-6 were found to be able to clear the fungal infection. 38 However, mice lacking IL23p19, one of the two subunits of IL-23, essential for Th17 cell expansion and function in mice 42 45 and humans, 46 48 displayed impaired IL-17A production and were highly susceptible to OPC. 39 49

Primary immunodeficiencies (PIDs) in humans

IL-17 immunity was shown to be essential for mucocutaneous protection against C. albicans in humans, in investigations of primary immunodeficiencies (PIDs) involving syndromic CMC, 39 50 53 as patients with these PIDs were found to have impaired IL-17 immunity. 39 52 Indeed, most patients with autosomal dominant (AD) hyper-IgE syndrome (AD-HIES) and STAT3 deficiency, 51 52 some patients with invasive fungal infections and autosomal recessive (AR) CARD9 deficiency 53 54 or with Mendelian susceptibility to mycobacterial diseases (MSMD) and AR IL-12p40 or IL-12Rβ1 deficiency 55 63 display CMC and have low proportions of IL-17A-producing T cells. 5 31 5 3 Indeed, most patients with AR autoimmune polyendocrine syndrome type 1 (APS-1) and AIRE deficiency display CMC and have high levels of neutralizing autoantibodies against IL-17A and IL-17F and/or IL-22. 63 64 These findings paved the way for the discovery of the first genetic etiologies of CMC disease (CMCD), an inherited condition affecting individuals without any of the abovementioned PIDs. 39 51 The pathogenesis of human CMC was eventually deciphered by studies of patients with CMC disease (CMCD), in which CMC is the only overt clinical sign. 51 Four genetic etiologies of CMCD have been described to date (Table 1). AR IL-17RA and AD IL-17F deficiencies were the first two genetic etiologies of CMCD to be discovered. 7 IL-17RA deficiency was complete, abolishing cellular responses to IL-17A and IL-17F homo- and heterodimers, 7 and to IL-17E (IL-25). 8

By contrast, IL-17F deficiency was partial, with impaired, but not abolished, cellular responses to the homo- and heterodimers containing the mutant IL-17F protein. 7 An AR deficiency of the IL-17R adaptor molecule ACT1 was later identified in two siblings with CMCD. 8 The patients’ fibroblasts failed to respond to IL-17A and IL-17F, and their T cells did not respond to IL-17E. 8 The most frequent genetic etiology of CMCD identified to date is caused by heterozygous gain-of-function mutations of the gene encoding the STAT1 transcription factor, which impair the development of IL-17-producing T cells. 9 22 Abnormally strong STAT1-dependent cellular responses to the IL-17 inhibitors IFN-α/β, IFN-γ, and IL-27, and/or to the STAT3-dependent IL-17 inducers IL-6, IL-21, and IL-23 may account for the poor development of IL-17-producing T cells observed in patients bearing such mutations. 8

Table 1 Clinical phenotypes of CMCD patients with inborn errors of IL-17 immunity

<table>
<thead>
<tr>
<th>Gene</th>
<th>Inheritance</th>
<th>Allele</th>
<th>Cytokines</th>
<th>Disease phenotype/infections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>IL-17A/F IL-17E</td>
<td></td>
</tr>
<tr>
<td>IL17F</td>
<td>AD</td>
<td>Partial loss-of-function (hypermorphic)</td>
<td>Impaired Normal?</td>
<td>CMC</td>
</tr>
<tr>
<td>IL17RA</td>
<td>AR</td>
<td>Complete loss-of-function (null)</td>
<td>Abolished</td>
<td>Abolished CMC</td>
</tr>
<tr>
<td>ACT1</td>
<td>AR</td>
<td>Complete loss-of-function (null)</td>
<td>Abolished</td>
<td>Abolished CMC</td>
</tr>
<tr>
<td>STAT1</td>
<td>AD</td>
<td>Gain-of-function (hypermorphic)</td>
<td>Normal?</td>
<td>Normal? Broader infectious phenotype</td>
</tr>
</tbody>
</table>

AD: autosomal dominant; AR: autosomal recessive; CMC: chronic mucocutaneous candidiasis.

IL-17 and other infections

Staphylococcus aureus skin infections have been reported in patients with AR IL-17RA or ACT1 deficiency  7 8 (Table 1). Indeed, the only patient with IL-17RA deficiency reported to date displayed S. aureus dermatitis at five months of age. 2 The two siblings with ACT1 deficiency suffered from recurrent blepharitis due to S. aureus. However, the phenotype of IL-17F-deficient patients is restricted to CMC with no other infectious disease, and these patients present no S. aureus skin disease, in particular. The S. aureus skin infections observed in IL-17RA- or ACT1-deficient patients may therefore be due to impaired IL-17A signaling and/or to other IL-17RA- and ACT1-dependent cytokines (e.g. IL-17E). Similarly, mice deficient for IL-17RA 2 70 72 and IL-17A 73 have been shown to be susceptible to cutaneous staphylococcal diseases, but mice lacking IL-17RC, ACT1, or IL-17F have not yet been tested. 39 Mice lacking IL-17RA or IL-17A have also been shown to be susceptible to Gram-positive bacteria, 74 65 Gram-negative bacteria, 76 77 viruses, 79 and parasites 40 injected intravenously or into joints. These findings suggest that IL-17 immunity may play non-redundant roles in host defense against these pathogens in mice, in these infection conditions. 2 By contrast, human IL-17 immunity is essential for host defense against mucocutaneous infections with C. albicans but appears to
be otherwise largely redundant against most other common pathogens in natura, as patients with inborn errors of IL-17 immunity display a narrow spectrum of pathogen susceptibility. Only patients with AD STAT1 gain-of-function (GOF) mutations display a broader infectious phenotype, with susceptibility to other fungal, bacterial and/or viral diseases reported in some cases. Indeed, some patients present fungal infections, such as severe dermatophytosis, disseminated histoplasmosis, or invasive coccidioidomycosis. Severe skin infections and unusual viral infections have also been reported: recurrent herpes virus infection, cytomegalovirus (CMV) infections, varicella zoster virus (VZV) infection, Epstein-Barr virus (EBV) infection, respiratory syncytial virus (RSV) bronchiolitis, chicken pox, and influenza infections. Bacterial infections, mostly caused by S. aureus, have also frequently been reported.

**CMC in humans following anti-17A treatment**

“Naturally” occurring antibodies (Abs) against IL-17 cytokines may be present in patients with APS-1, which suffer from CMC with no marked susceptibility to other pathogens. Indeed, high titers of neutralizing auto-Abs against IL-17A, IL-17F, and/or IL-22 have been detected in the serum of APS-1 patients. By contrast to the role of impaired IL-17A production in susceptibility to mucocutaneous candidiasis, IL-17 overproduction has been implicated in the pathogenesis of several immune-mediated inflammatory diseases in humans in which this cytokine has been found in the skin and/or joints of patients. These diseases include psoriasis, rheumatoid arthritis (RA), psoriatic arthritis (PsA), and uveitis. In some RA cohorts, higher IL-17A concentrations have been associated with a more severe clinical course. Several blockers of IL-17A, including the monoclonal anti-IL-17A Abs secukinumab and ixekizumab, and the monoclonal anti-IL-17RA Ab brodalumab, have been evaluated in phase II clinical trials and phase III studies. Secukinumab is a fully human immunoglobulin (Ig)-G1-k monoclonal Ab that neutralizes IL-17A and has been used to treat patients with psoriasis, RA, or uveitis. Ixekizumab is a humanized IgG4 anti-IL-17A monoclonal Ab that has been demonstrated to have meaningful clinical efficacy for the treatment of RA. The three randomized, double-blind, multicenter pivotal trials of secukinumab for the treatment of psoriasis collectively included 3,367 patients with moderate to severe chronic plaque psoriasis. Candida infections occurred in 4.7% of the patients on 300 mg secukinumab, 2.3% of those on 150 mg, and 1.2% of the etanercept (tumor necrosis factor, TNF) group. All cases of candidiasis in the group of patients treated with secukinumab were mild or moderate and easily treated. No other serious infections were reported. Treatment with recombinant IL-17 cytokines may be considered in patients with STAT1 GOF mutations or IL-17F deficiency, but not in patients with complete IL-17RA or ACT1 deficiency. However, preliminary tests should be performed to decrease the risk of the patient developing autoimmune diseases. Conversely, the use of anti-IL-17 Abs to treat patients with autoimmunity must be monitored carefully to prevent CMC.

**Conclusion**

Loss-of-function mutations of IL17RA, ACT1, and IL17F, and gain-of-function mutations of STAT1 are the four genetic etiologies of CMC described to date. Patients with these PIDs display recurrent or persistent oral candidiasis, with or without skin and/or nail involvement, from early infancy onwards. As in patients with APS-1 and high levels of neutralizing autoantibodies against IL-17A, IL-17F and/or IL-22, Candida infection was reported in patients with psoriasis treated with anti-IL17A Abs. Careful monitoring for candidiasis is thus essential during anti-IL-17 treatment.

**Conflicts of interest**

The authors declare that there are no conflicts of interest.

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