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Immunotherapy of aspergillosis

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Invited Review Article

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Abstract

Management of invasive aspergillosis in high risk patients remains a challenging effort. There is an increasing demand for novel therapeutic strategies aiming at enhancing or restoring antifungal immunity in immunocompromised patients. In this regard, modulating specific innate immune functions and vaccination are promising immunotherapeutic strategies. Recent findings have also provided a compelling rationale to assess the contribution of the individual genetic profile to the immunotherapy outcome. Altogether, integrating immunologic and genetic data may contribute to the optimization of therapeutic strategies exerting control over immune pathways, ultimately improving the management of fungal infections in high risk settings.

Aspergillus fumigatus is a ubiquitous mould that can adapt to a broad range of environmental conditions [1]. *A. fumigatus* can cause a number of diseases ranging from allergic to invasive, life-threatening forms of infection, which are strictly defined by the immune status of the host. The more severe forms of aspergillosis occur in specific clinical settings such as patients with hematological malignancies and prolonged and severe neutropenia, or patients on corticosteroid therapy and solid organ or stem cell transplantation. Management of invasive aspergillosis in high risk settings remains challenging due to intrinsic or acquired antifungal resistance, organ dysfunction preventing the use of particular agents and the deleterious effects of deregulated inflammation. Thus, there is an ever-increasing demand for novel therapeutic strategies to enhance or restore critical immune functions that may be applied to patients at high risk for fungal infections [1].

This review will highlight the conceptual advances made in cellular and immunological mechanisms underlying the host-fungus interaction and how this knowledge may be exploited for the successful design of immunotherapeutic interventions. The pathophysiology mechanisms underlying susceptibility to invasive aspergillosis are highlighted along with the awareness that the genetic make-up of the host may also critically contributes to risk for this disease [2-3].

Immunology of aspergillosis: from innate to adaptive immune responses

In the absence of major immune deficiencies, humans are relatively resistant to infection by *A. fumigatus* due to the immunological inertia of resting conidia [4]. This also implies that for most healthy humans, innate immune mechanisms are sufficient to clear the organism. These include the physical barriers of the respiratory tract and the activation of cellular [alveolar macrophages, dendritic cells (DCs) and recruited neutrophils] and humoral [pentraxin (PTX) 3 (see below), complement and cytokines] effector mechanisms of innate immunity (reviewed in [1]). Germination, however, exposes fungal-specific carbohydrates that serve as targets for invariant, germline-encoded pattern recognition receptors (PRRs)—such as Toll-like receptors (TLRs) and C-type lectin receptors— that are crucial for the initiation of innate and adaptive T helper (Th) immune responses [5]. Generation of a dominant Th1 response is essentially required for the expression of protective immunity to the fungus. Through the production of the signature cytokine IFN-γ, Th1 cells are instrumental for an optimal microbicidal activity of phagocytes. In contrast, allergic manifestations following inhalation of conidia due to overzealous Th2 responses are classical examples of the pathogenic role of T cell dysreactivity in fungal diseases. However, a further degree of complexity of cross-regulatory innate and adaptive Th pathways lies beyond the dichotomous Th1/Th2 model. Recent insights have suggested a role for Th17 cells, as a link between T cell inflammation and granulocytic influx observed in allergic airway inflammation [5]. The Th17 pathway, playing an inflammatory role previously attributed to uncontrolled Th1 cell reactivity and regulatory T cells (Tregs), capable of fine-tuning protective antimicrobial immunity in order to minimize harmful immune pathology, are now regarded as integral components of the immune response to the fungus (figure 1). The enzyme indoleamine 2,3–dioxygenase (IDO) and kynurenines pivotally contribute to this delicate balance by providing the host with immune mechanisms adequate for protection without necessarily eliminating fungal pathogens or causing an unacceptable level of tissue damage (see below). Specific antibodies to *A. fumigatus* have also been successfully detected in patients suffering from invasive aspergillosis, and their role in infection could be of interest. Indeed, a glyco-conjugate vaccine was found to efficiently immunize and protect mice against the infection [6], suggesting a role for antibody-mediated protection in aspergillosis.

Aspergillosis as an example of inflammatory disease

Although the inflammatory response to fungi may serve to limit infection, an overzealous or heightened inflammatory response may contribute to pathogenicity. This conceptual principle is best exemplified by the occurrence of severe fungal infections in patients with immunoreconstitution syndrome (IRS), an entity characterized by localized and systemic inflammatory reactions of varying degrees that have both beneficial and deleterious effects to the host [7]. Intriguingly, IRS responses are found after rapid resolution of immunosuppression, indicating that inflammatory responses can result in quiescent or latent infections manifesting as opportunistic mycoses. Thus, although host immunity is crucial in eradicating infection, immunological recovery can also be detrimental and may contribute towards worsening disease in opportunistic and non-opportunistic infections [7]. The association of persistent inflammation with intractable *Aspergillus* infection is common in non-neutropenic patients after allogeneic hematopoietic stem cell transplantation and in the hyper-IgE syndrome in which increased levels of pro-inflammatory gene transcripts have been described [8]. Therefore, the status of innate host immunity may contribute significantly to the pattern of diseases associated with fungal exposure. Corroborating these findings, recent works highlight the role of sterile inflammation – that is, (auto)inflammation caused by endogenous ligands – as a pathogenic determinant responsible for inflammation-driven pathology in aspergillosis [9]. Most prominently, in patients with chronic granulomatous disease (CGD), a hyperinflammatory phenotype and defective fungal—typically *A. fumigatus*—clearance have long been known to occur. This condition is crucially exemplified by recent findings in CGD mice, in which an intrinsic, genetically determined failure to control inflammation to sterile fungal components determines the animals' inability to resolve an actual infection with *A. fumigatus* [10]. These observations highlight a truly bipolar nature of the inflammatory process in infection. Early inflammation prevents or limits infection, but an uncontrolled response may eventually oppose disease eradication. A main implication of these findings is that, at least in specific clinical settings, it is an exaggerated inflammatory response that likely compromises a patient's ability to eradicate infection, and not an 'intrinsic' susceptibility to infection that determines a state of chronic or intractable disease.

Translating immunity into clinical perspectives

Colony stimulating factors (CSFs), granulocyte transfusions and cytokines. CSFs and cytokines, mainly IFN-γ, have been utilized in the clinical management of fungal diseases [11]. CSFs and granulocyte transfusions are used to augment the number and the function of circulating neutrophils in neutropenic patients. Studies in vitro, in animal models and limited patient data provide a rationale for adjunctive IFN-γ for invasive aspergillosis. The limited clinical experience to date shows a possible benefit of these cytokines, and further controlled clinical trials are needed to validate their routine use in cancer patients and stem-cell transplant recipients with invasive fungal infections who are likely to have a poor response to antifungal drug therapy [12]. Pairing IFN-γ with CSFs could be an option in the setting of refractory fungal disease, although clinical experience is anecdotal and the efficacy of this approach is not established (reviewed in [13]). Moreover, the disparate activity of CSFs on the immune system and types of immune responses generated, would suggest an activity for CSFs beyond their effects on hematopoiesis [14]. For instance, granulocyte-macrophage (GM)-CSF has recently been shown to play a key role in human DCs for activation of inflammatory Th1 and Th17 cells, and served a nonredundant function in the initiation of autoimmune inflammation [15]. Emerging evidence demonstrates the benefits of granulocyte transfusions to treat infections in patients after treatment with high-dose chemotherapy, particularly the chemotherapy associated with conditioning for hematopoietic stem cell transplant. The increased interest in the use of therapeutic granulocyte transfusion in recent years stems largely from improvements in donor mobilization methods. However, the evidence for clinical efficacy is limited to that of case reports and small series, and the results are not uniform. Randomized controlled clinical trials are needed to determine whether this therapy is useful in either clearing infections or prolonging survival [16-17].

T-cell therapy. T cell-mediated heterologous immunity to different pathogens is promising for the development of immunotherapeutic strategies. Fungus-specific $CD4^+$ Th1 immunity is an appealing strategy for antifungal therapy [18]. Recently, an immunogenic epitope of the *A. fumigatus* cell wall glucanase Crf1 was described as capable of inducing major histocompatibility complex class II restricted memory $CD4^+$ Th1 cells that are cross-reactive with *C albicans* [19]. These data illustrate the existence of T cell-based cross-protection for the distantly related clinically relevant fungal pathogens that may foster the

development of immunotherapeutic strategies. More recently, the usefulness of Treg-based immunotherapeutic approaches in allogeneic transplanted patients has also been investigated. Early adoptive therapy with Tregs followed by conventional T cells was demonstrated to favor immunologic reconstitution, besides preventing graft-versus-host disease without weakening the graft-versus-leukemia effect [20]. However, whether and how the adoptive immunotherapy with Tregs may compromise general immunity and blunt responses to other infectious agents remain to be fully assessed.

Anti- inflammatory therapies. Breakthroughs in understanding how immune homeostasis is established, maintained or disrupted in the presence of fungal exposure and/or colonization could be sources of new therapeutics and drugs targeting specific inflammatory or metabolic endpoints. In essence, limiting inflammation to stimulate a protective immune response to fungi should pave the way for rational design of novel immunomodulatory therapies. Below are examples of new therapeutics potentially capable of simultaneously activating antifungal resistance and taming overzealous inflammatory host responses.

PTX3. PTX3 is receiving great attention as a potential therapeutic agent with anti-inflammatory properties in aspergillosis. PTX3 is an opsonin that forms complexes on the conidial surface of *A. fumigatus*, thereby amplifying the innate immune response. Remarkably, PTX3 deficiency renders immunocompetent mice highly susceptible to *A. fumigatus* infection [21], whereas PTX3 administration protected against invasive aspergillosis in T cell–depleted allogeneic transplanted mice and potentiated the efficacy of amphotericin B. More recently, early administration of exogenous PTX3 was shown to enhance the conidiocidal activity of neutrophils and limit the inflammatory pathology in NADPH oxidase-deficient mice [22]. Finally, a number of predominantly non-coding polymorphisms have been identified in the *PTX3* gene which could be relevant in clinical fungal infections [23].

IDO and tryptophan metabolites. It has been shown that resistance and tolerance are two types of host defense mechanisms to increase fitness in response to fungi [5]. In experimental fungal infections, both defense mechanisms are activated through the delicate equilibrium between Th1 cells (which provide anti-fungal resistance mechanisms) and Tregs that limit the consequences of the associated inflammatory pathology [24]. IDO and kynurenines pivotally contribute to this delicate balance by providing the host with immune mechanisms adequate

for protection without necessarily eliminating fungal pathogens or causing an unacceptable level of tissue damage [24]. In their capacity to induce Tregs and inhibit Th17, IDO and kynurenines pivotally contribute to cell lineage decision in experimental fungal infections and revealed an unexpected potential in the control of inflammation, allergy and Th17-driven inflammation in these infections [24]. In this context, the Th17 pathway, which down-regulates tryptophan catabolism, may instead favor pathology [25] and serves to accommodate the seemingly paradoxical association of chronic inflammation with fungal disease. In experimental CGD, IL-17 neutralization increased fungal clearance, ameliorated inflammatory pathology and restored protective Th1 antifungal resistance [10]. Perhaps more importantly, complete cure and reversal of the hyperinflammatory CGD phenotype were achieved by administration of supplemental L-kynurenine, an early amino acid catabolite of L-tryptophan in the IDO-dependent pathway.

Thymosin α1. Innate signaling may either activate or limit, via induction of Tregs, adaptive immunity. This implies that selected PRR ligands might be useful candidate adjuvants to dampen inflammatory responses associated with infections. Thymosin α1 (Tα1), a naturally occurring thymic peptide, which is approved in 30 countries for treatment of a number of viral infections [26] and as an immune adjuvant, has been found to promote maturation of and cytokine production by DCs via TLR signaling [27]. By controlling the balance between the activity of immunogenic and tolerogenic DCs, Tα1 acted as an endogenous immune regulator capable of inducing protective immunity to *A. fumigatus*. In effect, Tα1 was found to induce IDO expression and production of kynurenines, thereby imprinting a tolerogenic program into inflammatory DCs [27]. Thus, instructive immunotherapy with Tα1 targeting IDO-competent DCs could allow for a balanced control of inflammation and tolerance in aspergillosis.

Targeting inflammatory pathways by siRNA. The intranasal administration of small interfering (si)RNA has opened new avenues in drug delivery and respiratory therapy [28]. Although the in vivo use of siRNA has been limited, they have huge potential as therapeutic agent given the absence of adverse immune reactions and systemic access. Adding to the potential of siRNA as therapeutic agents in the areas of cancer and viral infections, a recent study showed the potential of siRNA to attenuate inflammation in respiratory fungal infections [29]. In vivo targeting inflammatory (PI3K/Akt/mTOR) or anti-inflammatory (STAT3/IDO) pathways by intranasally delivered siRNA modified inflammation and immunity in aspergillosis. Thus, the screening of signaling pathways through a systems biology approach may be exploited for the development of siRNA therapeutics to attenuate

inflammation in respiratory fungal infections and diseases. Ultimately, because immunity is neither simply a set of discrete signaling pathways activated by pathogens nor a function of the host, the utilization of systems biology approaches is useful for the generation of new therapeutics that targets pathogenicity rather than microbial growth, the host-pathogen interface rather than the pathogen and promotes protective immune responses.

Vaccine development. With the exception of a killed spherule vaccine against coccidioidomycosis, no fungal vaccine trials have ever been conducted. However, the level of our understanding of fungal–host interactions has progressed to the point where vaccines against both primary fungal pathogens and the prevalent opportunistic fungi are becoming a reality [30]. In this regard, given the plasticity of the DC system in initiating disparate immune responses to fungi, vaccine-induced education of T cells could be regarded as a promising strategy to reduce the risk of fungal infection.

Genetic variability and immunotherapy outcome: towards personalized treatments?

Although the dissection of complex genetic traits modulating susceptibility to fungal infections is complex, the contribution of host genetics may hold the key to elucidate genetic markers for fungal infections and diseases occurring in high-risk patients. Understanding which patients are at highest risk of developing a life-threatening infection is at present a major deficiency, and genetic markers will probably assist in risk assessment. A number of studies have addressed the role of genetic variability in defining individual susceptibility to fungal infections [2-3]. A single nucleotide polymorphism (SNP) in TLR4 was first disclosed as a risk factor for chronic aspergillosis in immunocompetent individuals [31] and later, for invasive aspergillosis among unrelated allogeneic transplanted patients [32]. More recently, the stop codon polymorphism Y238X in dectin-1 was also found to contribute to an increased susceptibility to aspergillosis in the stem cell transplantation setting, a study which also uncovered the distinct contributions of the hematopoietic/nonhematopoietic cell compartments in the induction of immune protection to the fungus [33]. Although considerable efforts have been made in this direction, there is still the problem of limited power of the existing studies. Larger, well-designed trials, preferably performed in consecutive patients, are ultimately required to clarify the usefulness of genetic stratification of patients at risk for infection.

Perspectives in antifungal immunotherapy

The new discoveries in the field of fungal immunology have offered new grounds for a better comprehension of cells and immune pathways that are amenable to manipulation in patients with or at risk of fungal infections (figure 1). By influencing immune responses and inflammation, SNPs in immune genes may also affect the outcome of immunotherapeutic interventions. Therefore, devising immunotherapeutic strategies should not only consider the new conceptual advances on the knowledge of antifungal immunity, but also accommodate them from an immunogenetic standpoint. Identifying the cellular and molecular bases affected by genetic polymorphisms may prove a very powerful tool, maximizing the potential of therapeutic targets and prophylactic strategies exerting control over the outcome of immune pathways. Altogether, the genetic screening of at-risk patients may ultimately be used to individualize treatments through the formulation of new targeted and patient-tailored antifungal immunotherapeutics, likely improving the management and outcome of fungal infections.

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Transparency Declaration

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References

1 *Aspergillus fumigatus* and aspergillosis: ASM Press, 2009.

2 Cunha C, Romani L, Carvalho A. Cracking the Toll-like receptor code in fungal infections. *Expert Rev Anti Infect Ther*. 2010; **8**: 1121-1137.

3 Mezger M, Einsele H, Loeffler J. Genetic susceptibility to infections with *Aspergillus fumigatus*. *Crit Rev Microbiol*. 2010; **36**: 168-177.

4 Aimanianda V, Bayry J, Bozza S, et al. Surface hydrophobin prevents immune recognition of airborne fungal spores. *Nature*. 2009; **460**: 1117-1121.

5 Romani L. Immunity to fungal infections. *Nat Rev Immunol*. 2011; **11**: 275-288.

6 Torosantucci A, Bromuro C, Chiani P, et al. A novel glyco-conjugate vaccine against fungal pathogens. *J Exp Med*. 2005; **202**: 597-606.

7 Singh N, Perfect JR. Immune reconstitution syndrome associated with opportunistic mycoses. *Lancet Infect Dis*. 2007; **7**: 395-401.

8 Holland SM, DeLeo FR, Elloumi HZ, et al. STAT3 mutations in the hyper-IgE syndrome. *N Engl J Med*. 2007; **357**: 1608-1619.

9 Sorci G, Giovannini G, Riuzzi F, et al. The danger signal S100B integrates pathogen- and danger-sensing pathways to restrain inflammation. 2011; *PLoS Pathog*. **7**: e1001315.

10 Romani L, Fallarino F, De Luca A, et al. Defective tryptophan catabolism underlies inflammation in mouse chronic granulomatous disease. *Nature*. 2008; **451**: 211-215.

11 Roilides E, Lamaignere CG, Farmaki E. Cytokines in immunodeficient patients with invasive fungal infections: An emerging therapy. *Int J Infect Dis*. 2002; **6**: 154-163.

12 Safdar A. Strategies to enhance immune function in hematopoietic transplantation recipients who have fungal infections. *Bone Marrow Transplant*. 2006; **38**: 327-337.

13 Segal BH, Kwon-Chung J, Walsh TJ, et al. Immunotherapy for fungal infections. *Clin Infect Dis*. 2006; **42**: 507-515.

14 Stull DM. Colony-stimulating factors: Beyond the effects on hematopoiesis. *Am J Health Syst Pharm*. 2002; **59**: S12-20.

15 Codarri L, Gyulveszi G, Tosevski V, et al. Rorgammat drives production of the cytokine GM-CSF in helper T cells, which is essential for the effector phase of autoimmune neuroinflammation. *Nat Immunol*. 2011; **12**: 560-567.

16 Massey E, Paulus U, Doree C, Stanworth S. Granulocyte transfusions for preventing infections in patients with neutropenia or neutrophil dysfunction. *Cochrane Database Syst Rev*. 2009: CD005341.

17 Price TH. Granulocyte transfusion: Current status. *Semin Hematol*. 2007; **44**: 15-23.

18 Tramsen L, Schmidt S, Roeger F, Koehl U, Lehrnbecher T. Challenges and prospects of adoptive immunotherapy in prevention and treatment of opportunistic mycoses in hematologic transplant recipients. *Curr Infect Dis Rep*. 2010; **12**: 444-449.

19 Stuehler C, Khanna N, Bozza S, et al. Cross-protective Th1 immunity against *Aspergillus fumigatus* and *Candida albicans*. *Blood*. 2011; **117**: 5881-5891.

20 Di Ianni M, Falzetti F, Carotti A, et al. Tregs prevent GVHD and promote immune reconstitution in HLA-haploidentical transplantation. *Blood*. 2011; **117**: 3921-3928.

21 Garlanda C, Hirsch E, Bozza S, et al. Non-redundant role of the long pentraxin PTX3 in anti-fungal innate immune response. *Nature*. 2002; **420**: 182-186.

22 D'Angelo C, De Luca A, Zelante T, et al. Exogenous pentraxin 3 restores antifungal resistance and restrains inflammation in murine chronic granulomatous disease. *J Immunol*. 2009; **183**: 4609-4618.

23 Chiarini M, Sabelli C, Melotti P, et al. PTX3 genetic variations affect the risk of *Pseudomonas aeruginosa* airway colonization in cystic fibrosis patients. *Genes Immun*. 2010; **11**: 665-670.
24 Romani L, Puccetti P. Protective tolerance to fungi: The role of IL-10 and tryptophan catabolism. *Trends Microbiol*. 2006; **14**: 183-189.
25 Zelante T, De Luca A, Bonifazi P, et al. IL-23 and the Th17 pathway promote inflammation and impair antifungal immune resistance. *Eur J Immunol*. 2007; **37**: 2695-2706.
26 Goldstein AL. From lab to bedside: Emerging clinical applications of thymosin alpha 1. *Expert Opin Biol Ther*. 2009; **9**: 593-608.
27 Pierluigi B, D'Angelo C, Fallarino F, et al. Thymosin alpha1: The regulator of regulators? *Ann N Y Acad Sci*. 2010; **1194**: 1-5.
28 Behlke MA. Progress towards in vivo use of siRNAs. *Mol Ther*. 2006; **13**: 644-670.
29 Bonifazi P, D'Angelo C, Zagarella S, et al. Intranasally delivered siRNA targeting PI3K/Akt/mTOR inflammatory pathways protects from aspergillosis. *Mucosal Immunol*. 2010; **3**: 193-205.
30 Cutler JE, Deepe GS, Jr., Klein BS. Advances in combating fungal diseases: Vaccines on the threshold. *Nat Rev Microbiol*. 2007; **5**: 13-28.
31 Carvalho A, Pasqualotto AC, Pitzurra L, Romani L, Denning DW, Rodrigues F. Polymorphisms in toll-like receptor genes and susceptibility to pulmonary aspergillosis. *J Infect Dis*. 2008; **197**: 618-621.
32 Bochud PY, Chien JW, Marr KA, et al. Toll-like receptor 4 polymorphisms and aspergillosis in stem-cell transplantation. *N Engl J Med*. 2008; **359**: 1766-1777.
33 Cunha C, Di Ianni M, Bozza S, et al. Dectin-1 Y238X polymorphism associates with susceptibility to invasive aspergillosis in hematopoietic transplantation through impairment of both recipient- and donor-dependent mechanisms of antifungal immunity. *Blood*. 2010; **116**: 5394-5402.

Figure legend

Figure 1. Immunotherapy in aspergillosis. The figure exemplifies recent findings on the innate and adaptive immune responses to *Aspergillus fumigatus* and the possible strategies of immune interventions. Most of these immunotherapies have only been evaluated in animal models of aspergillosis. PRRs, pattern recognition receptors; EC, epithelial cells; PMN, polymorphonuclear cells; Mø, macrophages; Abs, antibodies. See the text for details.

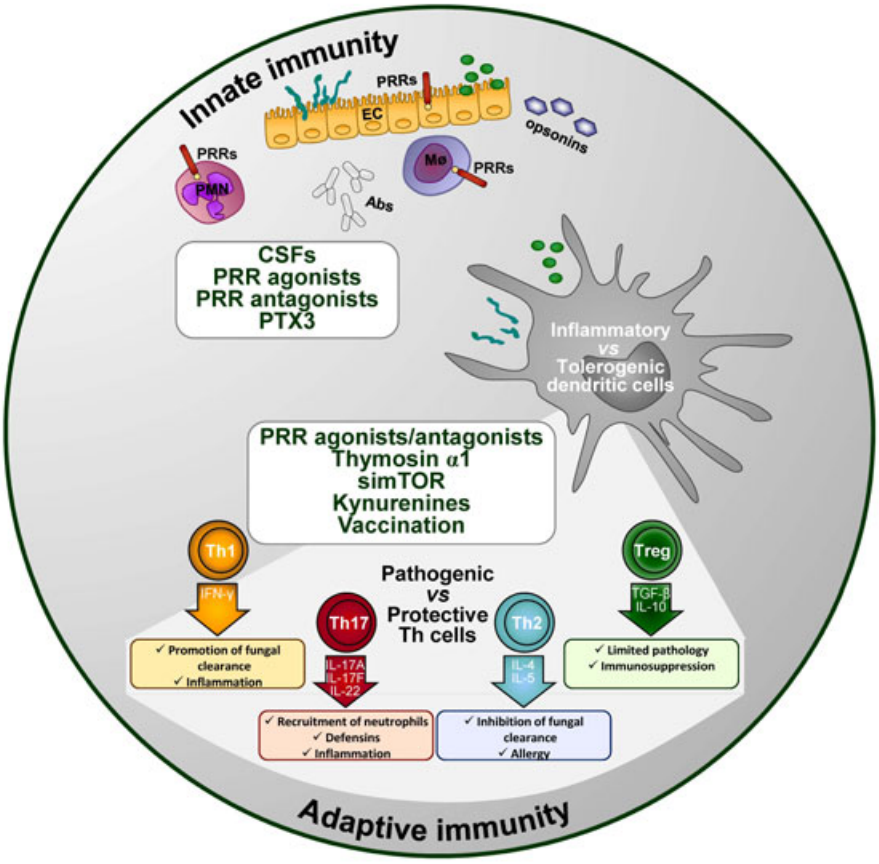
Innate immunity
PRRs
EC
opsonins
PRRs
PMN
Mø
PRRs
Abs
CSFs
PRR agonists
PRR antagonists
PTX3
Inflammatory
vs
Tolerogenic
dendritic cells
PRR agonists/antagonists
Thymosin α1
simTOR
Kynurenines
Vaccination
Th1
IFN-γ
✓ Promotion of fungal clearance
✓ Inflammation
Pathogenic
vs
Protective
Th cells
Th17
IL-17A
IL-17F
IL-22
✓ Recruitment of neutrophils
✓ Defensins
✓ Inflammation
Th2
IL-4
IL-5
✓ Inhibition of fungal clearance
✓ Allergy
Treg
TGF-β
IL-10
✓ Limited pathology
✓ Immunosuppression
Adaptive immunity

Figure 1