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Reduced IL-2 response from peripheral blood mononuclear cells exposed to bacteria at 6 months of age is associated with elevated total-IgE and allergic rhinitis during the first 7 years of life

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1. Introduction

Reduced numbers and function of regulatory T-cells (Tregs) have been demonstrated in autoimmune and allergic diseases, suggesting that a dysregulated Treg system contributes to the pathogenesis of these conditions [1–4]. Interleukin 2 (IL-2) is critical for the development and survival of Tregs [5–7] and a possible role of the IL-2/Treg interplay in allergy has been suggested by a study showing that reduced IL-2 expression by cord blood CD4+(+) T cells associated with decreased Tregs and increased risk of food allergy in childhood [8].

In the Copenhagen Prospective Studies on Asthma in Childhood 2000 (COPSAC2000) mother-child cohort we conducted repeated clinical assessments including total-IgE, specific-IgE, and allergic rhinitis through age 7 and biobanking of peripheral blood mononuclear cells (PBMCs) isolated from the infants at age 6 months. Recently, we investigated the PBMC response to in vitro stimulations with pathogenic airway bacteria was associated with development of allergy-outcomes in early childhood.

Methods: PBMCs were isolated at age 6 months in 331 infants from the Copenhagen Prospective Studies on Asthma in Childhood 2000 (COPSAC2000) mother-child cohort, and subsequently stimulated with H. influenzae, M. catarrhalis and S. pneumoniae in in vitro cultures. Levels of cytokines (IL-2, IL-10, IFN-γ, TNF-α, IL-5, IL-13 and IL-17A) were determined in the supernatant by electrochemiluminescence immunoassays. The immune profiles were analyzed for association with development of total-IgE, allergic sensitization and rhinitis during the first 7 years of life using regression models and principal component analysis (PCA).

Findings: An attenuated IL-2 response to stimulation with H. influenzae (p = 0.011) and M. catarrhalis (p = 0.027) was associated with elevated total-IgE at age 7, which was confirmed in a multivariate PCA model including all cytokine measurements (PC2, p = 0.032). An immune profile with both reduced IL-2 and elevated IL-5 was associated with increased risk of allergic rhinitis (PC3, p = 0.038). We found no associations with development of allergic sensitization.

Interpretation: A reduced IL-2 response from PBMCs exposed to common pathogenic airway bacteria at age 6 months was associated with elevated total-IgE and allergic rhinitis during the first 7 years of life. These findings suggest that suppressed Treg activity in early life may herald onset of allergy in early childhood, which could be a target for low-dose IL-2 trials in the future.

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Abbreviations: COPSAC, Copenhagen Prospective Studies on Asthma in Childhood; PBMC, Peripheral Blood Mononuclear Cell; PCA, Principal Component Analysis; Treg, regulatory T cell; SPT, Skin prick test.

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It is well known that T regulatory cell (Tregs) play important roles in maintaining homeostasis of the immune system. Interleukin 2 (IL-2) is crucial for the development and survival of Tregs acting via its high affinity receptor CD25 and it has been demonstrated that low-dose IL-2 therapy results in significant expansion and activation of Tregs. It has been shown in randomized placebo-controlled trials that low dose IL-2 therapy is safe in humans and has the capacity to successfully control the manifestation of several diseases related to imbalanced immune responses, including hepatits C virus-mediated vasculitis, graft-versus-host disease, alopecia areata and type 1 diabetes. Recently, it has been shown that a disturbed IL-2/Treg interplay may be of importance in childhood allergy development as reduced IL-2 expression by cord blood CD4(+) T cells was associated with decreased numbers of Tregs and increased risk of subsequent food allergy in the Barwon Infant study. Further, findings from a mouse model showed that low dose IL-2 treatment could dampen the allergic inflammatory process by inducing expansion and activation of Tregs. These findings suggest a potential application of low dose IL-2 therapy for prevention and treatment of childhood allergy, but further human studies are needed to disentangle the role of IL-2 expression in early life in relation to the development of allergic outcomes.

Evidence before this study

It is well known that T regulatory cell (Tregs) play important roles in maintaining homeostasis of the immune system. Interleukin 2 (IL-2) is crucial for the development and survival of Tregs acting via its high affinity receptor CD25 and it has been demonstrated that low-dose IL-2 therapy results in significant expansion and activation of Tregs. It has been shown in randomized placebo-controlled trials that low dose IL-2 therapy is safe in humans and has the capacity to successfully control the manifestation of several diseases related to imbalanced immune responses, including hepatits C virus-mediated vasculitis, graft-versus-host disease, alopecia areata and type 1 diabetes. Recently, it has been shown that a disturbed IL-2/Treg interplay may be of importance in childhood allergy development as reduced IL-2 expression by cord blood CD4(+) T cells was associated with decreased numbers of Tregs and increased risk of subsequent food allergy in the Barwon Infant study. Further, findings from a mouse model showed that low dose IL-2 treatment could dampen the allergic inflammatory process by inducing expansion and activation of Tregs. These findings suggest a potential application of low dose IL-2 therapy for prevention and treatment of childhood allergy, but further human studies are needed to disentangle the role of IL-2 expression in early life in relation to the development of allergic outcomes.

Added value of this study

In this study we investigated the functional immune properties of peripheral blood mononuclear cells (PBMCs) from 6-month-old healthy infants stimulated with pathogenic airway bacteria and show that immune responses characterized by reduced production of IL-2 are associated with development of elevated total-IgE levels and allergic rhinitis during the first 7 years of life. This suggests the existence of suppressed Treg activity in early life heralding the onset of allergy outcomes during early childhood, which may be reversed by low dose IL-2 therapy. The aim of the current study is to analyze the relationship between the PBMC response to bacterial stimulations and the development of allergy-related endpoints during the first 7 years of life, hypothesizing a protective role of IL-2.

2. Materials and methods

2.1. Study cohort

This study is part of the ongoing COPSAC2000 prospective mother-child cohort of 411 children born to mothers with asthma [11]. The children were enrolled at age 1 month, excluded children born before gestational week 36 and children suffering from any respiratory disorder before enrollment. The children were followed prospectively at the COPSAC clinical research unit with regular follow-up visits every 6 months till age 7 and at episodes with respiratory symptoms. The clinical research unit was the primary health care facility for diagnosis and treatment of any respiratory symptoms, strictly adhering to validated algorithms [12].

The study was approved by the Copenhagen Ethics Committee (KF 01-289/96), the Danish Data Protection Agency (2002-41-2434), and followed the principles of the Declaration of Helsinki. Written and oral informed consent was obtained from the parents at enrollment.

2.2. Bacterial stimulation of PBMCs

The bacterial stimulations of PBMCs was previously described in details [9,10]. Briefly, PBMCs were isolated by density centrifugation from blood samples collected at 6 months and stored for up to 12 years at -140 °C. After thawing, the cells were stimulated with UV-inactivated H. influenzae, M. catarrhalis, and S. pneumoniae (50 μg/ml) or blank sterile culture media alone in U-bottomed 96-well plates at 5 × 10⁶ cells/well (200 μl total volume/well) for 40 h at 37 °C and 5% CO₂ in a humidified incubator. Supernatants were harvested and stored at -80 °C until quantification of IL-2, IL-10, IFN-γ, TNF-α, IL-5, IL-13 and IL-17A levels by customized multiplex immunoassays from MesoScale Discovery read on a Sector Imager 6000 (MSD, Gaithersburg, MD, USA). All assays were highly sensitive with a detection limit below 1 pg/ml.

3. T cell immune phenotyping

The composition of the T cell compartment was analyzed on freshly thawed unstimulated PBMCs (5 × 10⁶ cells) using flow cytometry. Staining and flow cytometry analysis were performed using the following antibody panel: CD3/eFlour450, CD8/FITC, TCRVa24-Ja18/PerCP-eFlour710, CD127/APC-eFlour780 (eBioscience, San Diego, CA), CD25/PC7, TCRγδ/PE (Beckman Coulter, Brea, CA) and CD4/V500 (BD Bioscience, San Jose, CA). T cell subsets were identified by a predefined gating strategy and analyzed in a blinded manner: Helper (CD3⁺CD4⁺), cytotoxic (CD3⁺CD8⁺), regulatory (CD3⁺CD25⁺γδ), and regulatory (CD3⁺CD127⁺CD25⁺γδ) T cells, and invariant NK (CD3⁺TCRVo24-Jε18⁺) T cells. All population frequencies were calculated relative to the CD3⁺ T cell compartment.

3.1. Allergy-related endpoints

Total-IgE level was determined at 6 years by ImmunoCAP (Pharmacia Diagnostics AB, Uppsala, Sweden) and analyzed as a continuous variable.

Allergic sensitization was assessed at 6 years by skin prick tests (SPT) and measurements of specific-IgE against house dust mites, cat, dog, horse, birch, grass, mugwort, and molds as previous detailed [13]. SPT was done using allergen extracts (ALK Abello, Soluprick® SQ, Copenhagen, Denmark) defining a positive test as any wheal ≥ 3 mm. Specific-IgE levels were measured with ImmunoCAP (Thermo Fisher Scientific, Uppsala, Sweden), defining a positive test as any specific-IgE level ≥ 0.35kUa/L. Sensitization was analyzed as a dichotomized variable, separately for SPT and specific-IgE as the overlap between test results is poor at young age [14].

Allergic rhinitis at age 7 was diagnosed by the COPSAC pediatricians based on a parental interview on the child’s history of symptoms [15]. Significant sneezing or blocked or runny nose affecting the wellbeing of the child in the past 12 months in periods without cold or flu defined rhinitis. The diagnosis required sensitization and congruence between symptoms and allergen exposure.

3.2. Statistical analysis

Initially, supernatant levels of cytokines in response to bacterial stimulations were adjusted by subtracting the baseline levels of
cytokines secreted by PBMCs incubated with sterile media. Thereafter, the levels were square root-transformed. If an individual did not produce a measurable cytokine response in PBMCs after bacterial stimulation (non-responders), the cytokine level was set to zero.

First, we analyzed the association between the cytokines released upon bacterial stimulations at 6 months and total-IgE level (log-transformed), allergic sensitization by SPT (yes/no) and elevated specific-IgE (yes/no), and allergic rhinitis (yes/no) during the first 7 years of life using linear and logistic regression models. The associations with outcomes for cytokines from each bacterial stimulation were analyzed using forward stepwise selection while retaining IL-2. If the final model had multiple independent variables they were compared with a null model by ANOVA for goodness of fit. If only IL-2 was retained in the final model, the hypothesis test for its coefficient was used as assessment of goodness of fit. Only the models with significant overall p-values (≤0.05) are discussed in detail.

Thereafter, we conducted a data-driven principal component analysis (PCA) on the 21 independent variables (3 bacterial stimulation x 7 different cytokines) to capture immune patterns in the data, using principal component 1 to 4 (PC1–4) from the model for association analyses with the outcomes.

We also analyzed the association between T cell subsets and allergy-related outcomes. T cell composition data was transformed by isometric log ratio (ilr) using sequential binary partitioning and their association with outcomes was analyzed by multiple regression models [16].

All analyses were conducted with R version 3.4.2 [17]. The results are reported with 95% CI and p-values ≤0.05 were considered statistically significant.

4. Results

4.1. Baseline characteristics

A total of 331 (81%) of the 411 infants in the cohort had PBMCs collected at age 6 months, which were subsequently exposed to H. influenzae, M. catarrhalis, and S. pneumoniae for assessment of the immune response by measuring supernatant cytokine levels. The T cell immune phenotyping and immune responses are described in Tables 1–2. Of the 331 infants, 259 (78%) had measurements of total-IgE (mean level, 117.6 IU/mL), 270 (82%) had SPT (N = 251) and/or slgE (N = 259) with 100 (30%) being sensitized to one or more allergen either by SPT (N = 40) and/or slgE (N = 94). Allergic rhinitis was assessed in 254 (77%) with a prevalence of 13% (N = 34) by age 7 years.

A comparison between children with vs. without immune response data has previously been published showing no differences [9,10].

4.2. Bacteria-induced immune response and allergy-related outcomes

4.2.1. Total-IgE

Multiple regression analyses showed inverse associations between IL-2 production in response to H. influenzae and M. catarrhalis at age 6 months and total-IgE level at age 6 years: IL-2-coefficient	i = −0.183 [95% CI; −0.324, −0.043], p = 0.011 and IL-2-coefficient	i = −0.150 [−0.282, −0.018], p = 0.027, respectively. The IL-2 association was only seen in response to the Gram-negative bacteria H. influenzae (Ptest = 0.028) and M. catarrhalis (Ptest = 0.024), whereas the model using cytokine data in response to the Gram-positive bacteria S. pneumoniae was not better than the null model (Ptest = 0.139): IL-2-coefficient	i = 0.151 [0.001, 0.301], p = 0.0503 (Fig. 1).

Besides IL-2, the production of IFN-γ and TNF-α in response to H. influenzae and M. catarrhalis was positively associated with total-IgE level: IFN-γ-coefficient	i = 0.019 [0.000, 0.0367], p = 0.046, and TNF-α-coefficient	i = 0.159 [0.027, 0.290], p = 0.019, respectively.

The result of a PCA analysis to identify individual cytokine profiles in response to the bacteria is depicted in Fig. 2 and Fig. 1. The PCA association analysis for total-IgE confirmed the findings from the regression models. The cytokine pattern in PC2 from M. catarrhalis was inversely associated with total-IgE level (p = 0.032) and the same trend was seen for PC2 from H. influenzae stimulation (p = 0.051); i.e. higher total-IgE was associated with a decreasing score dominated by IL-2 (Fig. 2).

4.2.2. Allergic sensitization

Higher IL-5 secretion in response to S. pneumoniae was significantly associated with sensitization by sIgE at age 6: ORmc = 0.495 [0.273, 0.898], p = 0.021, and ORmc = 0.429 [0.197, 0.933], p = 0.033; i.e. higher IL-2 and IL-13 production reduced the risk of allergic rhinitis. We also found that elevated IL-5 in response to all the bacterial stimulations increased the risk of allergic rhinitis: ORhi = 1.954 [1.037, 3.681], ORhi = 0.038, ORmc = 1.569 [1.056, 2.330], p = 0.026, and ORmc = 1.614 [1.070, 2.434], p = 0.022. The multiple regression models were all significantly better than the null models: χ2 = 0.048 for H. influenzae, p = 0.017 for M. catarrhalis, and χ2 = 0.046 for S. pneumoniae (Fig. 1).

The results from the PCA supported the main findings from the regression analyses regarding IL-5 and IL-2, but not for IL-13. We found an inverse association between development of allergic rhinitis and the immune pattern in PC3 upon M. catarrhalis stimulation.
PBMCs collected at age 6 months was associated with elevated total-
M. catarrhalis
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\text{colors and bigger dot size, otherwise the colors were faint and the dots were smaller. Positive SPT} = \text{positive skin prick test, hi} = \text{H. in}
\]

model statistics (Odds Ratio (OR) for binary outcomes, coefficients for continuous outcome and their associated 95% confidence intervals) for significant ones were shown in solid colors and bigger dot size, otherwise the colors were faint and the dots were smaller. Positive SPT = positive skin prick test, hi = H. influenzae, mc = M. catarrhalis, sp = S. pneumoniae.

\[
\text{(p} = 0.038), \text{i.e. lower IL-2 and higher IL-5 from PBMCs at 6 months increased the risk of allergic rhinitis at age 7. In addition, a decreasing PC4 score from the H. influenzae stimulation was significantly associated with risk of allergic rhinitis, i.e. lower IL-17A and higher IFN-\gamma release increased the risk of allergic rhinitis (p} = 0.048)
\]

(Fig. 2).

4.2.4. Sensitivity analysis

As many of the children did not produce any IL-5 in PBMCs after bacterial stimulations (IL-5 non-responders), we conducted a sensitivity analysis excluding these (Table e1). This showed similar results for the univariate association between IL-5 and allergic rhinitis by age 7: ORhi = 2.532 [1.127, 5.690], p = 0.025, ORmc = 3.231 [1.274, 8.200], p = 0.014, and ORsp = 1.729 [1.084, 2.757], p = 0.021, and the multiple regression models were also significantly better than the null models: \( p_{\text{chisq}} = 0.040 \) for H. influenzae, \( p_{\text{chisq}} = 0.001 \) for M. catarrhalis, and \( p_{\text{chisq}} = 0.048 \) for S. pneumoniae (Fig. e2). The PCA results were consistent showing an inverse association between allergic rhinitis and the immune pattern in PC3 upon stimulations from both M. catarrhalis (\( p = 0.036 \)) and H. influenzae (\( p = 0.038 \)) (Fig. e3).

4.3. T cell compartment composition

To study if the cytokine response profiles were related to an underlying difference in T cell subsets, we examined the T cell compartment composition in relation to the allergy-outcomes. The relative ratios of \( \gamma \delta \) T cells and iNKT cells amongst all T cells were associated with total-IgE level at age 6, but in opposite directions with an inverse association for iNKT cells (\( p = 0.030 \)), and positive association for \( \gamma \delta \) T cells (\( p = 0.022 \)) (Fig. 3, Fig. e4). No associations between the relative ratio of Tregs and development of allergy-related outcomes were observed (Fig. 3).

5. Discussion

5.1. Main findings

An attenuated IL-2 response to stimulation with the common Gram-negative pathogenic airway bacteria H. influenzae and M. catarrhalis in PBMCs collected at age 6 months was associated with elevated total-IgE at age 6 years. Furthermore, both reduced IL-2 and increased IL-5 production were associated with a higher risk of developing allergic rhinitis during the first 7 years of life. Altogether, these findings suggest a role of diminished IL-2 and increased IL-5 in development of allergy-related traits in early childhood.

5.2. Strengths and limitations

This is the first prospective cohort study to investigate infant’s bacterial immune responses in PBMCs, which was done in a comprehensive manner by analyzing several cytokines of the Treg, Th1, Th2, and Th17 cells. The prospective nature of our study and the storage of PBMCs at age 6 months provide a unique possibility to investigate functional immunological properties in infancy before onset of allergy-related outcomes. As the PBMCs were collected in asymptomatic infants before onset of allergic disease, the bacterial immune response is unlikely to be affected by immune dysfunction caused by ongoing disease-driven inflammation.

It is an advantage of the study that the children participating in the COPSAC2000 cohort solely used the COPSAC research pediatrics for diagnosis and treatment of any asthma and allergy-related disease. All diagnoses were done based on rigid standardized algorithms providing highly reliable homogeneous clinical outcomes.

It is a limitation that this was an in vitro study that may not reflect the complexity of the immune responses in vivo. Importantly, many of the infants stored PBMCs did not produce a measurable IL-5 response to any of the bacterial stimulations. However, analyses including the IL-5 non-responders as zeros as well as analyses excluding the non-responders showed similar associations with the clinical endpoints.

It is a limitation that the results are based on one concentration of antigen performed at one time point (40 h culture). Therefore, we are not able to determine how the results would look like at different time points and by stimulating with different concentrations, which is particularly important for IL-2, which is consumed in the cultures. However, this would have been of greater importance if we had not detected an association between IL-2 PBMC responses and allergy-outcomes.

Finally, it is a limitation that all the children participating in the cohort were born to mothers with a history of asthma, which may hamper the external validity of our findings.
5.3. Interpretation

In this study, we aim to identify immune patterns in infancy in response to different bacteria in relation with development of allergic disorders in the first 7 years of life. The bacterial stimulations were chosen as we previously demonstrated that one-month-old infants colonized in the airways with *H. influenzae*, *M. catarrhalis*, and/or *S. pneumoniae* had an increased risk of asthma at age 5 years [18]. However, no direct link was shown between neonatal airway colonization with these bacteria and allergic outcomes, but studies indicate that environmental exposure to certain bacteria or bacterial components like lipopolysaccharide, which is contained in *H. influenzae* and *M. catarrhalis*, are associated with risk of allergic sensitization in childhood [19–21].

We speculate that our finding of a reduced IL-2 production in concert with increased IL-5 to stimulations with the Gram-negative bacteria *H. influenzae* and *M. catarrhalis* may be caused by imbalanced Treg and Th2 populations and thereby increase the risk of developing allergic diseases. This finding may be of clinical importance as low-dose IL-2 therapy is being investigated with the purpose of expanding the Treg population in several diseases. We did not observe similar findings when analyzing the cytokine responses from the Gram-positive *S. pneumoniae* stimulation, which may be due to the fact that this bacteria does not contain the innate immune ligand lipopolysaccharide.

Recent clinical trials have studied the tolerability and efficacy of low-dose IL-2 therapy in the treatment of autoimmune disorders and graft-versus-host disease [22–25]. All trials reported the therapy to be safe and effective in mediating sustained expansion of systemic Tregs with clinically relevant improvement in patients with HCV-induced vasculitis [22], alopecia areata [25], and graft-versus-host disease [24]. We speculate that low-dose IL-2 therapy may have a beneficial role on allergy and propose initiation of clinical trials in children with allergy and subsequently trials investigating low-dose IL-2 as a possible therapeutic intervention or a prophylactic regimen in high-risk infants. Due to the proposed early window of immune programming for regulatory T cell development [26], it might be speculated to be even more important to propagate Treg development in early infancy, once an impaired IL-2 production has been detected. We here addressed the question of IL-2 production in PBMCs collected at 6 months of age, as bacteria-specific T cells will have been expanded at this age if the child has been exposed to the given bacteria in vivo. This is in contrast to studies performed on cord blood. We selected a relatively short stimulation protocol of 40 h
Further experimental studies of i.e. allergen-specific stimulations of human PBMCs are needed to determine whether IL-2 therapy should solely be targeted to the allergic phenotype.

Higher IL-13 production upon bacterial stimulation of the PBMCs was observed to reduce the risk of allergic rhinitis, which was however not significant in the multivariate PCA approach. This is an unexpected finding as co-expression of IL-4, IL-13 and IL-5 are normally observed in patients with ongoing symptoms of rhinitis. A non-coordinate expression of IL-4, IL-13 and IL-5 can occur when distinct Th2 clones produce each cytokine individually. Thus, the discrepancy in expression of IL-5 and IL-13 may suggest a transient expression pattern associated with the initial stage of Th2 priming as we investigated the response from stimulated PBMCs in 6-month-old asymptomatic infants long before onset of any symptoms of allergic rhinitis.

Our T cell compartment data showed an association between the composition of γδ T cells and total-IgE level suggesting a possible function of γδ T cells in the development of allergic diseases. Such association has previously been reported in children with atopic dermatitis aged 1 to 10 years, whereas no association was observed for total-IgE level within these children with atopic dermatitis [33]. Finally, we also identified an inverse association between the composition of iNKT cells and total-IgE, which is consistent with previous findings in adult asthmatics [34].

6. Conclusion

Reduced IL-2 production and increased IL-5 from PBMCs in response to bacterial stimulations in early life were associated with development of elevated total-IgE and allergic rhinitis during the first 7 years of life. This finding is of possible clinical relevance as experimental studies have shown that low-dose IL-2 therapy can restore immune tolerance by the expansion of Tregs.

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Conflict of interests

The authors declare no conflicts of interest.

Author contributions

The guarantor of the study is HB who is responsible for the integrity of the work as a whole, from conception and design to conduct of the study and acquisition of data, analysis and interpretation of data and writing of the manuscript. HB had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. BC and NW were responsible for data analysis and wrote the first draft of the manuscript. AMS, JML, AT, SBP, MAR, JS and KB contributed to design of the study, interpretation of data and writing of the manuscript. JML, AT and SBP were responsible for generating the PMBC immune response data. All co-authors have contributed substantially to the analyses and/or interpretation of the data and have provided important intellectual input and approval of the final version of the manuscript. No honorarium, grant, or other forms of payment was given to anyone to produce the manuscript.
References

[1] Illi S, von Mutius E, Liu J, et al. Impairment of T-regulatory cells in cord blood of atopic mothers. J Allergy Clin Immunol 2008;121(6):1409–1–9 e13 https://doi.org/10.1016/j.jaci.2008.04.010.

[2] Sakaguchi S, Ono M, Setoguchi R, et al. Foxp3+CD25+CD4+ natural regulatory T cells in dominant self-tolerance and autoimmune disease. Immuno Rev 2006;212:8–27. https://doi.org/10.1111/j.0105-2896.2006.00427.x.

[3] Kelchtermans H, De Kleere B, Mitera T, et al. Defective CD4+CD25+ regulatory T cell functioning in collagen-induced arthritis: an important factor in pathogenesis, counter-regulated by endogenous IFN. Arthritis Res Ther 2005;7(2):R402–15. https://doi.org/10.1186/ar1500.

[4] Grindebacke H, Wing K, Andersson AC, Suri-Payer E, Rudin A. Defective suppression of Th2 cytokines by CD4+CD25+ regulatory T cells in birch allergies during birch pollen season. Clin Exp Allergy 2004;34(9):1364–72. https://doi.org/10.1111/j.1365-2222.2004.02067.x.

[5] Zheng SG, Wang P, Gray JD, Wang J, Horwitz DA. IL-2 is essential for TGF- to convert naive CD4+CD25– cells to CD4+Foxp3+ regulatory T cells and for expansion of these cells. J Immunol 2014;187(4):2018–27. https://doi.org/10.4049/jimmunol.14-0047.

[6] Fontenot JD, Rasmussen JP, Gavin MA, Rudensky AY. A function for interleukin 2 in naive CD4+CD25– cells to CD25+Foxp3+ regulatory T cells and for expansion of these cells. J Immunol 2004;178(4).2018. https://doi.org/10.1155/2014/108742.

[7] Yu A, Liu J, Altman NH, Malek TR. A low interleukin-2 receptor signaling threshold supports the development and homeostasis of T regulatory cells. Immunity 2009;30(2):204–17. https://doi.org/10.1016/j.immuni.2008.11.014.

[8] Zhang Y, Collier F, Naselli G, et al. Cord blood monocyte-derived inflammatory cytokines suppress IL-2 and induce nonclassic “Th2-type” immunity associated with development of food allergy. Sci Trans Med 2016;8(321). https://doi.org/10.1126/scitransmed.aad2322.

[9] Birch S, Thysen AH, Brix S, Larsen JM, Bisgaard H, Rasmussen MA. Children with asthma by school age display aberrant immune responses to pathogenic airway bacteria as infants. J Allergy Clin Immunol 2014;133(4):1008–1013.e4. https://doi.org/10.1016/j.jaci.2014.01.010.

[10] Vissing NH, Larsen JM, Rasmussen MA, et al. Susceptibility to lower respiratory infections in childhood is associated with perturbation of the cytokine response to pathogenic airway bacteria. Pediatr Infect Dis J 2016;35(5):561–6. https://doi.org/10.1097/INF.0000000000001092.

[11] Bisgaard H. The Copenhagen Prospective Study on Asthma in Childhood (COPSAC): design, rationale, and baseline data from a longitudinal birth cohort study. Ann Allergy Asthma Immunol 2004;93(4):381–9. https://doi.org/10.1016/j.jpain.2008.11.014.

[12] Vigneron J, Brimaud F, Churlaud G, et al. Low-dose IL-2 induces regulatory T cell-mediated control of experimental food allergy. J Immunol 2014;193(1):349–55. https://doi.org/10.4049/jimmunol.1301731.

[13] Atarashi K, Shima TT, Inoaka A, et al. Induction of colonic regulatory T cells by indigenous Clostridium species. Science 2011;331(6012):337–40. https://doi.org/10.1126/science.1196031.

[14] Smith K, McCoy KD, Macpherson AJ. Use of xenic animals in studying the adaptation of mammals to their commensal intestinal microbiota. Semin Immunol 2007;19(2):59–69. https://doi.org/10.1016/j.smim.2006.10.002.

[15] Vatanen T, Kostic AD, D’Hennezel E, et al. Variation in microbiome LPS immunogenicity contributes to autoimmunity in humans. Cell 2016;165(4):841–53. https://doi.org/10.1016/j.cell.2016.04.007.

[16] Bengsston L, Bresson G, Nyden A, et al. The Copenhagen Prospective Study on Asthma in Childhood (COPSAC): effects of low-dose recombinant interleukin-2 therapy in type 1 diabetes. Diabetes 2015;64:2172–83. https://doi.org/10.2337/db14-1322.

[17] Round JL, Mazmanian SK. The gut microbiota shapes intestinal immune responses during health and disease. Nat Rev Immunol 2009;9(5):313–23. https://doi.org/10.1038/nri2515.

[18] Al-Nabhani Z, Dulauroy S, Marques R, et al. Weaning reaction to microbiota is restored by IL-2. J Allergy Clin Immunol 2014;133(4):977–86. https://doi.org/10.1016/j.jaci.2014.01.010.

[19] Vatanen T, Kostic AD, D’Hennezel E, et al. Low-dose IL-2 induces regulatory T cell responsiveness of regulatory T cells in graft-versus-host disease. N Engl J Med 2010;362(5):387–401. https://doi.org/10.1056/NEJMoa1002057.

[20] Vatanen T, Kostic AD, D’Hennezel E, et al. Induction of colonic regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[21] Atarashi K, Shima TT, Inoaka A, et al. Induction of colonic regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[22] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[23] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[24] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[25] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[26] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.

[27] Al-Nabhani Z, Dulauroy S, Marques R, et al. Selective IL-2 responsiveness of regulatory T cells by indigenous Clostridium species. Science 2011;331(2):337–40. https://doi.org/10.1126/science.1196031.