



IL1RL1 gene variations are associated with asthma exacerbations in children and adolescents using inhaled corticosteroids

To the editor,

Asthma, one of the most common chronic diseases in childhood, is caused by interactions between genes and environmental factors. The mainstay of treatment is daily use of inhaled corticosteroids (ICS), which are the most effective medication for controlling asthma symptoms and preventing (severe) exacerbations. ICS use reduces both hospitalizations and mortality rates¹ and improves asthma control; reflected in forced expiratory volume in 1 second (FEV₁) levels and fraction of exhaled nitric oxide (FeNO). These effects are particularly observed in asthma patients with eosinophilic, type 2 airway inflammation.² However, responses to ICS are heterogeneous, which while controversial, possibly reflect genetic associations.^{3,4}

Genome-wide association studies (GWAS) have reproducibly found the *Interleukin 1 receptor like 1* (*IL1RL1*, *ST2*) gene to be associated with asthma susceptibility.⁵ *IL1RL1* single-nucleotide polymorphisms (SNPs) and *IL1RL1* expression levels have been associated with blood eosinophils and markers of Th2 type inflammation.^{6,7} However, the influence of *IL1RL1* SNPs on the effectiveness of asthma treatment has not been investigated. Since the IL-33/*IL1RL1* pathway has been associated with eosinophilic, type 2, inflammation, we hypothesized that *IL1RL1* SNPs may affect corticosteroid treatment response in asthma patients. Since *IL1RL1*-a functions as a decoy receptor to dampen IL-33-induced signaling, genetically determined low levels of *IL1RL1*-a may predispose to enhanced IL-33-induced inflammation with consequently more exacerbations.

In the current study, we investigated whether *IL1RL1* gene variants are associated with asthma exacerbations (based on ER visits/hospitalizations and courses of oral corticosteroid [OCS] use), questionnaire-based asthma control and FeNO levels in asthma patients using ICS. Furthermore, we aimed to identify whether there is a pharmacogenetic effect of *IL1RL1* variants on change in FeNO levels and FEV₁% predicted in asthma patients after 4-6 weeks of ICS treatment.

After close inspection of the Linkage Disequilibrium structure of *IL1RL1*, we selected 6 *IL1RL1* SNPs that tag important LD blocks in *IL1RL1* ($r^2 > .8$) with SNPs previously found to be associated with asthma⁵; rs13431828, rs1041973, rs1420101, rs1946131, rs1921622, and rs10204137 (Table S1). Cross-sectional *IL1RL1* SNP

discovery analysis was performed in ICS treated asthmatic children, mainly of European ancestry, from the Pharmacogenetics of Asthma Medication in Children: Medication with Anti-inflammatory effects (PACMAN) cohort (N = 820) using logistic and linear regression models. We replicated FDR corrected significant findings ($P < .05$) in four different cohorts collaborating within the Pharmacogenomics in Childhood Asthma (PiCA) consortium,⁸ one Hispanic/Latino study; Genes-Environment and Admixture in Latino Americans (GALA II, N = 876) study, one African American population; Study of African Americans, Asthma, Genes, and Environments (SAGE, N = 525), and two European studies ($\geq 96\%$ European ancestry); the Effectiveness and Safety of Treatment with Asthma Therapy in children (ESTATE, N = 197) and SLOVENIA (N = 104). In addition, we performed a meta-analysis (N = 2412). The longitudinal effect of *IL1RL1* on FeNO levels and FEV₁% predicted upon ICS treatment in asthmatic children and adults was assessed in the SLOVENIA cohort. Conditional analysis was performed in PACMAN to assess the independent effects of the *IL1RL1* SNPs.

A detailed representation of the included cohorts and the allele frequencies of the *IL1RL1* SNPs are provided in Tables S2 and S3, respectively. In PACMAN, we found a significant association between four of the six SNPs (rs13431828, rs1420101, rs1921622, and rs10204137) with ER visits and "any exacerbation" (Table 1A-C), which were selected for the replication study. Sensitivity analyses on Dutch ethnicity, atopy, and medication adherence did not change these results. We did not observe an association with questionnaire-based asthma control or FeNO measurements (Table S4A-B).

In GALA II, we replicated our findings with significant results with the same direction of effect for rs13431828, rs1420101, and rs1921622 on ER visits/hospitalizations and "any exacerbation." Rs10204137 showed a significant association with "any exacerbation" (Table 1A-C). In SAGE, rs1921622 was associated with "any exacerbation" but the direction of the effect differed when compared to PACMAN. No association between *IL1RL1* and questionnaire-based asthma control was found. In the smaller SLOVENIA and ESTATE studies, no significant cross-sectional or longitudinal associations were found (Table S5).

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2019 The Authors. *Allergy* published by John Wiley & Sons Ltd

TABLE 1 Results of associations of *IL1RL1* SNPs with ER visits/hospitalizations, OCS use, and “any exacerbation” per study and meta-analysis

A.										
SNP	Allele (R/E) ^a	ER visits/hospitalisations								
		PACMAN (n = 698)			GALA II (n = 876)			SAGE (n = 525)		
		OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b
rs13431828	T/C	2.78 (1.11-6.94)	.02	.04	1.45 (1.04-2.03)	.03	.04	1.18 (0.88-1.58)	.26	.52
rs1041973	A/C	1.35 (0.77-2.37)	.30	.30						
rs1420101	G/A	1.61 (1.05-2.47)	.02	.04	1.28 (1.04-1.58)	.02	.04	0.90 (0.69-1.17)	.45	.60
rs1946131	G/A	1.47 (0.81-2.68)	.20	.24						
rs1921622	G/A	1.89 (1.18-3.03)	.01	.04	1.30 (1.06-1.59)	.01	.04	0.74 (0.55-0.99)	.05	.20
rs10204137	G/A	1.37 (0.87-2.16)	.18	.24	1.24 (0.99-1.56)	.06	.06	1.01 (0.76-1.35)	.92	.92

B.										
SNP	Allele (R/E) ^a	OCS use								
		PACMAN (n = 720)			GALA II (n = 876)			SAGE (n = 525)		
		OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b
rs13431828	T/C	2.70 (1.08-6.79)	.03	.09	1.25 (0.87-1.79)	.23	.65	0.93 (0.68-1.27)	.65	.70
rs1041973	A/C	1.52 (0.86-2.66)	.15	.27						
rs1420101	G/A	1.32 (0.88-1.98)	.18	.27	1.10 (0.86-1.40)	.49	.65	0.78 (0.57-1.05)	.09	.20
rs1946131	G/A	1.08 (0.57-2.02)	.83	.83						
rs1921622	G/A	1.20 (0.78-1.86)	.41	.49	1.10 (0.88-1.38)	.44	.65	0.76 (0.54-1.08)	.10	.10
rs10204137	G/A	1.69 (1.05-2.73)	.03	.09	1.03 (0.81-1.32)	.80	.80	0.94 (0.69-1.28)	.70	.70

C.										
SNP	Allele (R/E) ^a	Any exacerbation								
		PACMAN (n = 720)			GALA II (n = 876)			SAGE (n = 525)		
		OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b
rs13431828 ^c	T/C	2.63 (1.33-5.18)	.006	.03	1.63 (1.14-2.32)	.009	.01	1.04 (0.78-1.39)	.80	.80
rs1041973	A/C	1.28 (0.84-1.96)	.26	.26						
rs1420101	G/A	1.52 (1.08-2.13)	.01	.03	1.35 (1.06-1.72)	.01	.01	0.83 (0.63-1.10)	.18	.36
rs1946131	G/A	1.37 (0.83-2.25)	.22	.26						
rs1921622	G/A	1.45 (1.03-2.04)	.03	.04	1.35 (1.08-1.70)	.009	.01	0.67 (0.50-0.90)	.009	.03
rs10204137 ^d	G/A	1.52 (1.05-2.18)	.02	.04	1.29 (1.00-1.66)	.04	.04	0.91 (0.68-1.21)	.50	.66

Note: Bold-faced results are FDR corrected significant results ($P < .05$). Missing values mean the SNP was not present in the study.

Abbreviations: CI, confidence interval; ER, Emergency room; OCS, oral corticosteroid; OR, odds ratio; SNP, single-nucleotide polymorphism.

^aR = reference allele, E = effect allele.

^bFDR corrected P value.

^crs13431828 was not present in ESTaTe, and rs3771180 was used as a surrogate marker (LD $r^2 = 1$).

^drs10204137 was not present in ESTaTe, and rs4988956 was used as a surrogate marker (LD $r^2 = 1$).

Meta-analysis of the 4 *IL1RL1* SNPs carried through to replication showed statistically significant results for rs13431828. The C allele of rs13431828 was associated with ER visits/hospitalizations (OR = 1.32, $P = .02$) and increased risk of “any exacerbations” (1.31, $P = .02$; Table 1A-C, Figure 1). No evidence of heterogeneity was found ($Q = 3.6$, $P = .33$).

Conditional analysis in PACMAN on rs13431828, rs1420101, rs1921622, and rs10204137 for “any exacerbation” indicated

that rs13431828 was the most independently associated SNP (Table S6).

These results provide new evidence that children and adolescents with the *IL1RL1* risk alleles are prone to more exacerbations than children with the protective genotypes, while using ICS. This extends previous findings that SNPs in *IL1RL1* are important in different asthma phenotypes, with more prominent effect in studies investigating

SLOVENIA (n = 187)			ESTATe (n = 104)			Meta-analysis (n = 2421)			
OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	N
1.20 (0.62-2.35)	.57	.77	1.01 (0.18-5.72)	.99	.99	1.32 (1.08-1.62)	.005	.02	2412
1.09 (0.67-1.76)	.72	.77	1.35 (0.56-3.25)	.51	.94	1.16 (1.01-1.34)	.03	.06	2412
0.93 (0.57-1.51)	.77	.77				1.13 (0.97-1.31)	.13	.17	2308
0.75 (0.46-1.22)	.24	.77	0.81 (0.34-1.94)	.63	.94	1.10 (0.95-1.29)	.18	.18	2412

SLOVENIA (n = 187)			ESTATe (n = 104)			Meta-analysis (n = 2421)			
OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	N
1.60 (0.57-4.47)	.36	.90	1.15 (0.46-2.85)	.77	.77	1.13 (0.91-1.41)	.24	.78	2412
0.95 (0.49-1.85)	.89	.90	0.68 (0.34-1.36)	.28	.77	0.98 (0.84-1.16)	.90	.90	2412
0.81 (0.41-1.59)	.54	.90				1.00 (0.84-1.18)	.96	.96	2308
1.04 (0.52-2.05)	.90	.90	1.15 (0.58-2.27)	.70	.70	1.07 (0.90-1.27)	.39	.39	2412

SLOVENIA (n = 187)			ESTATe (n = 104)			Meta-analysis (n = 2421)			
OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	OR (95% CI)	P	P ^b	N
1.19 (0.66-2.12)	.73	.83	1.09 (0.47-2.56)	.83	.86	1.31 (1.07-1.59)	.007	.02	2412
1.05 (0.65-1.67)	.83	.83	0.85 (0.48-1.53)	.60	.60	1.14 (0.98-1.32)	.07	.14	2412
0.84 (0.52-1.35)	.47	.83				1.08 (0.92-1.25)	.31	.31	2308
0.81 (0.50-1.30)	.38	.83	0.95 (0.53-1.70)	.86	.86	1.11 (0.96-1.30)	.14	.18	2412

childhood-onset asthma.⁵ Rs1420101 has been specifically linked to the type 2-high asthma phenotype,⁶ as well as to increased eosinophil numbers in peripheral blood.⁹

We observed replicable associations of the same *IL1RL1* risk alleles in the Caucasian (PACMAN) and Hispanic/Latino (GALA II) population, but not in the African American study population (SAGE). This could be due to differences in ethnicity between study groups and LD patterns

in this gene, suggested by the observed differences in allele frequency between the cohorts (see Table S3). It is possible that our results may have been influenced by factors other than currently included in the model such as inhalation technique or respiratory infections, but as such data were not available in all cohorts these were not considered.

Different mechanisms may explain our findings. Firstly, *IL1RL1* SNPs may modify the asthma phenotype into a more severe

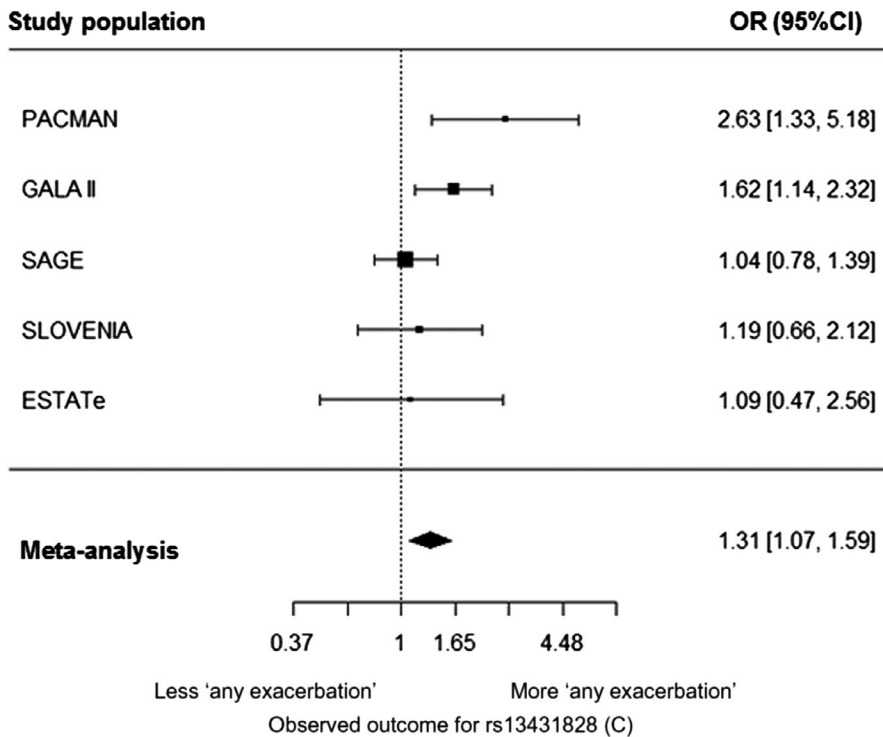


FIGURE 1 Forest plot showing the meta-analysis result of the association between the *IL1RL1* SNP rs13431828 (C) and 'any exacerbation' ($P = 0.02$). Included cohorts are PACMAN, GALA II, SAGE, SLOVENIA and ESTATE. Odds ratio (OR) and 95% confidence intervals (CI) are shown for the effect alleles (additive model). 'Any exacerbation' was defined as ER visits/hospitalizations and/or OCS use

phenotype, with more severe exacerbations, which are insufficiently treated with the ICS dosages prescribed to the children in this study. The risk alleles described in our study for rs13431828 (C), rs1420101 (T), rs1921622 (A), and rs10204137 (A) were previously associated with lower *IL1RL1* blood methylation levels and lower serum *IL1RL1*-a levels,⁷ indicating that the associated SNPs are important for regulation of *IL1RL1* expression. Another mechanism to explain our results is that *IL1RL1* may have a direct pharmacogenetic interaction with steroids resulting in reduced efficacy of the steroids. Rs10204137 is a missense mutation and has been associated with increased *IL1RL1*-a expression, which induces *IL-33* expression and enhances *IL-33* responsiveness.¹⁰ Moreover, rs10204137 tags an LD block that contains 5 nonsynonymous coding SNPs that result in changes to four amino acids in the intracellular domain of *IL1RL1*-b. These coding changes affect the Toll/interleukin-1 receptor (TIR) domain of the intracellular part of the *IL1RL1* protein, which plays an important role in *IL-33* induced signal transduction by *IL1RL1*. This triggers a signaling cascade that eventually results in the activation of downstream mitogen-activated protein kinases and transcription factors, such as nuclear factor κ B (NF- κ B) and activator protein-1.⁵ Through this pathway, asthmatic children carrying the risk allele of rs10204137 may be more sensitive to *IL-33*. As *IL1RL1* is expressed on effector cells of the type-2 immune response such as mast cells, eosinophils, basophils, Th2 cells and ILC2 cells,¹¹ an increased sensitivity to *IL33* will contribute to an exaggerated type-2 inflammatory response after viral or allergen exposure.

Secondly, *IL1RL1* may have a direct pharmacogenetic interaction with steroids resulting in reduced efficacy of the steroids. A recent study on ulcerative colitis found an association between dexamethasone and upregulation of soluble *IL1RL1* transcription mediated via

interaction of the steroid with the glucocorticoid-responsive element in the *IL1RL1* promoter patients carrying polymorphisms.¹² To gain more insight into the mechanism underlying our finding, future studies should be performed in larger cohorts or with the use of biobank data.

This study shows that an *IL1RL1* SNP effect is present in asthmatic children using ICS. This highlights the potential investigating if novel treatment strategies targeting the *IL33/IL1RL1* pathway could be used as add-on asthma treatment in patients using ICS.

ACKNOWLEDGMENTS

We would like to thank the participants and their parents of the studied cohorts for their participation. We also would like to acknowledge the field workers, data managers, and scientific collaborators dedicated to these cohorts. The authors acknowledge the GALA II and SAGE investigators (Kelley Meade, Harold J. Farber, Pedro C. Avila, Denise Serebrisky, Shannon M. Thyne, Emerita Brigino-Buenaventura, William Rodriguez-Cintrón, Saunak Sen, Rajesh Kumar, Michael Lenoir, Luisa N. Borrell, and Jose R. Rodriguez-Santana), the recruiters, participants, and the study coordinator Sandra Salazar. We thank as well the ESTATE investigators (Pharmo: Ron Herings, Annemarie Janse, Jettie Overbeek, Josine Kuiper. IPCI: Katia Verhamme, Hettie Janssens, Johan de Jongste, Miriam Sturkenboom).







CONFLICT OF INTEREST

N. Hernandez-Pacheco received a grant from Instituto de Salud Carlos III (ISCIII) and was co-funded by the European Social Funds from the European Union (ESF) "ESF invests in your future." MC Nawijn received a grant from GSK during the conduct of this study and outside the submitted work. ME Engelkes received a grant from ZonMw. K. M. Verhamme received a grant from ZonMw and she works for a research group who in the past received

unconditional grants from: Yamanouchi, Pfizer/Boehringer Ingelheim, Novartis and GSK. M Pino-Yanes received a grant from the Spanish Ministry of Economy, Industry and Competitiveness and a grant from Instituto de Salud Carlos III (ISCIII). AH Maitland-van der Zee received an unrestricted research grant from GSK, and Boehringer Ingelheim. She also received a grant from ERANET ERACOSYSMED, and she participated in an advisory board for Astra Zeneca. DS Postma declares that the University of Groningen has received money for DS Postma regarding a grant for research from Astra Zeneca, Chiesi, Genentec, GSK and Roche. Fees for consultancies were given to the University of Groningen by Astra Zeneca, Chiesi, and GSK. GH Koppelman received grants from the Lung Foundation of the Netherlands, the Ubbo Emmius Foundation, during the conduct of the study; and he received grants from Lung Foundation of the Netherlands, GSK, Tetri Foundation, Vertex, TEVA the Netherlands, outside the submitted work. GHK participated in an advisory board meeting of GSK. The rest of the authors declare that they have no relevant conflict of interests.

FUNDING INFORMATION

The PACMAN study was supported by an unrestricted grant from GlaxoSmithKline (GSK), whereas genetic analysis for the present study was supported by a Lung Foundation of the Netherlands grant no. AF3.2.09.081JU. FND was supported by the Ubbo Emmius Foundation. The GALA II and SAGE studies were funded by the Sandler Family Foundation, the American Asthma Foundation, the RWJF Amos Medical Faculty Development Program, Harry Wm. and Diana V. Hind Distinguished Professor in Pharmaceutical Sciences II, National Institutes of Health (1R01HL117004, R01HL128439, R01HL135156, and 1X01HL134589), National Institute of Health and Environmental Health Sciences (R01ES015794 and R21ES24844), the National Institute on Minority Health and Health Disparities (1P60MD006902, U54MD009523, and 1R01MD010443), and the Tobacco-Related Disease Research Program under Award Number 24RT-0025 to EGB. This work was also funded by Instituto de Salud Carlos III (AC15/00015), through Strategic action for Health Research (AES) and European Community (EC) within the Active and Assisted Living (ALL) Programme framework, and by the SysPharmPedia grant from the ERACoSysMed first joint Transnational cCall from the European Union under the Horizon 2020. NH-P was funded by a fellowship (FI16/00136) from Instituto de Salud Carlos III (ISCIII) and co-funded by the European Social Funds from the European Union (ESF) "ESF invests in your future" and MP-Y was supported by the Ramón y Cajal Program (RYC-2015-17205) by the Spanish Ministry of Economy, Industry, and Competitiveness. For the SLOVENIA study, the authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P3-0067) and from SysPharmPedia grant, co-financed by Ministry of Education, Science and Sport of the Republic of Slovenia. The ESTate project was supported by a ZonMw Grant No 113201006. The PiCA study was overall supported by ERACoSysMed 1st Joint Transnational Call (SysPharmPedia).

F. Nicole Dijk¹ 
 Susanne J. Vijverberg^{2,3} 
 Natalia Hernandez-Pacheco^{4,5} 
 Katja Repnik^{6,7}
 Leila Karimi⁸
 Marianna Mitratza³
 Niloufar Farzan^{2,3}
 Martijn C. Nawijn⁹
 Esteban G. Burchard^{10,11}
 Marjolein Engelkes⁸
 Katia M. Verhamme⁸
 Uroš Potočnik^{6,7}
 Maria Pino-Yanes^{4,5,12} 
 Dirkje S. Postma¹³
 Anke-Hilse Maitland-van der Zee^{2,3,14} 
 Gerard H. Koppelman¹ 

¹Department of Pediatric Pulmonology and Pediatric Allergology, Beatrix Children's Hospital, Groningen Research Institute for Asthma and COPD (GRIAC), University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

²Department of Respiratory Medicine, Amsterdam University Medical Centers, University of Amsterdam, Amsterdam, The Netherlands

³Division of Pharmacoepidemiology and Clinical Pharmacology, Faculty of Science, Utrecht University, Utrecht, The Netherlands

⁴Research Unit, Hospital Universitario N.S. de Candelaria, Universidad de La Laguna, Santa Cruz de Tenerife, Spain

⁵Genomics and Health Group, Department of Biochemistry, Microbiology, Cell Biology and Genetics, Universidad de La Laguna, La Laguna, Tenerife, Spain

⁶Center for Human Molecular Genetics and Pharmacogenomics, Faculty of Medicine, University of Maribor, Maribor, Slovenia

⁷Laboratory for Biochemistry, Molecular Biology and Genomics, Faculty for Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia

⁸Department of Medical Informatics, Erasmus University Medical Center, Rotterdam, The Netherlands

⁹Laboratory of Allergology and Pulmonary Diseases, Pathology and Medical Biology, Groningen Research Institute for Asthma and COPD (GRIAC), University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

¹⁰Department of Medicine, University of California, San Francisco, CA, USA

¹¹Department of Bioengineering and Therapeutic Sciences, University of California, San Francisco, CA, USA

¹²CIBER de Enfermedades Respiratorias, Instituto de Salud Carlos III, Madrid, Spain

¹³Department of Pulmonary Diseases, Groningen Research Institute for Asthma and COPD (GRIAC), University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

¹⁴Department of Pediatric Respiratory Medicine and Allergy, Emma's Children Hospital, Academic Medical Center (AMC), University of Amsterdam, Amsterdam, The Netherlands

Correspondence

Gerard H. Koppelman, Pediatric Pulmonology and Pediatric Allergology, Beatrix Children's Hospital, University Medical Center Groningen, PO Box 30.001, 9700 RB Groningen, The Netherlands.
Email: g.h.koppelman@umcg.nl

ORCID

F. Nicole Dijk  <https://orcid.org/0000-0001-7680-4951>
Susanne J. Vijverberg  <https://orcid.org/0000-0002-4579-4081>
Natalia Hernandez-Pacheco  <https://orcid.org/0000-0002-6313-1847>
Maria Pino-Yanes  <https://orcid.org/0000-0003-0332-437X>
Anke-Hilse Maitland-van der Zee  <https://orcid.org/0000-0002-0414-3442>
Gerard H. Koppelman  <https://orcid.org/0000-0001-8567-3252>

Maitland-van der Zee and Koppelman contributed equally.

REFERENCES

1. Global Initiative for Asthma. Global strategy for asthma management and prevention. 2018. www.ginasthma.org
2. Woodruff PG, Modrek B, Choy DF, et al. T-helper Type 2 – driven inflammation defines major subphenotypes of asthma. *Am J Respir Crit Care Med*. 2009;180:388-395.

3. Kersten ETG, Koppelman GH. Pharmacogenetics of asthma: toward precision medicine. *Curr Opin Pulm Med*. 2017;23:12-20.
4. Mosteller M, Hosking L, Murphy K, et al. No evidence of large genetic effects on steroid response in asthma patients. *J Allergy Clin Immunol*. 2017;139:797-803.
5. Grotenboer NS, Ketelaar ME, Koppelman GH, Nawijn MC. Decoding asthma: translating genetic variation in IL33 and IL1RL1 into disease pathophysiology. *J Allergy Clin Immunol*. 2013;131:856-865.
6. Gordon ED, Palandra J, Wesolowska-Andersen A, et al. IL1RL1 asthma risk variants regulate airway type 2 inflammation. *JCI Insight*. 2016;1:e87871.
7. Dijk FN, Xu C, Melén E, et al. Genetic regulation of IL1RL1 methylation and IL1RL1-a protein levels in asthma. *Eur Respir J*. 2018;51:1701377.
8. Farzan N, Vijverberg SJ, Andiappan AK, et al. Rationale and design of the multiethnic pharmacogenomics in childhood asthma consortium. *Pharmacogenomics*. 2017;18:931-943.
9. Gudbjartsson DF, Bjornsdottir US, Halapi E, et al. Sequence variants affecting eosinophil numbers associate with asthma and myocardial infarction. *Nat Genet*. 2009;41:342-347.
10. Brusselle GG, Maes T, Bracke KR. Eosinophils in the spotlight: eosinophilic airway inflammation in nonallergic asthma. *Nat Med*. 2013;19:977-979.
11. Saluja R, Ketelaar ME, Hawro T, Church MK, Maurer M, Nawijn MC. The role of the IL-33/IL-1RL1 axis in mast cell and basophil activation in allergic disorders. *Mol Immunol*. 2015;63:80-85.
12. Díaz-Jiménez D, Núñez L, De La Fuente M, et al. A functional IL1RL1 variant regulates corticosteroid-induced sST2 expression in ulcerative colitis. *Sci Rep*. 2017;7:1-14.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.