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1 **A novel role for cilia function in atopy: *ADGRVI* and *DNAH5* interactions**

2
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40 **ABSTRACT**

41 **Background:** Atopy, an endotype underlying allergic diseases, has a substantial genetic
42 component.

43 **Objective:** Our goal was to identify novel genes associated with atopy in asthma-ascertained
44 families.

45 **Methods:** We implemented a three-step analysis strategy in three datasets: The Epidemiological
46 study on the Genetics and Environment of Asthma (EGEA) dataset: 1,660 subjects; The Saguenay-
47 Lac-Saint-Jean (SLSJ) dataset: 1,138 subjects; and The Medical Research Council (MRC) dataset:
48 446 subjects). This strategy included a single-SNP genome-wide association study (GWAS), the
49 selection of related gene pairs based on statistical filtering of GWAS results and text-mining
50 filtering using GRAIL and SNP-SNP interaction analysis of selected gene pairs.

51 **Results:** We identified the 5q14 locus, harboring the adhesion G protein-coupled receptor V1
52 (*ADGRV1*) gene, that showed genome-wide significant association with atopy (rs4916831;
53 $P_{\text{meta}}=6.8 \times 10^{-9}$). Statistical filtering of GWAS results followed by text-mining filtering revealed
54 relationships between *ADGRV1* and three genes showing suggestive association with atopy ($P \leq 10^{-4}$).
55 SNP-SNP interaction analysis between *ADGRV1* and these three genes showed significant
56 interaction between *ADGRV1* rs17554723 and two correlated SNPs (rs2134256 and rs1354187)
57 within dynein axonemal heavy chain 5 (*DNAH5*) gene ($P_{\text{meta-int}}=3.6 \times 10^{-5}$ and 6.1×10^{-5} , that met the
58 multiple-testing corrected threshold of 7.3×10^{-5}). Further conditional analysis indicated that
59 rs2134256 alone accounted for the interaction signal with rs17554723.

60 **Conclusion:** As both *DNAH5* and *ADGRV1* contribute to function of cilia, this study suggests that
61 cilia dysfunction may represent a novel mechanism underlying atopy. Combining GWAS and
62 epistasis analysis driven by statistical and knowledge-based evidence represents a promising
63 approach for identifying new genes involved in complex traits.

64 **Key Messages:**

- 65 • *ADGRVI* genetic variants are associated with atopy in asthma families
- 66 • Interaction between *ADGRVI* and *DNAH5* variants is associated with atopy; these two
- 67 genes are involved in ciliary function
- 68 • Use of a strategy that combines genome-wide association analysis and epistasis analysis
- 69 driven by statistical and knowledge-based evidence can successfully identify new genes
- 70 underlying complex traits.

71 **Capsule summary:**

72 This study in three family-based studies identified association between *ADGRVI* and atopy and

73 interaction between *ADGRVI* and *DNAH5*, two genes that contribute to ciliary functions.

74 **Key words:** atopy, asthma, genetics, genome-wide association study, gene-gene interaction, text-

75 mining, *ADGRVI*, *DNAH5*, ciliary function

76 **Abbreviations:**

77 *ADGRVI*: adhesion G protein-coupled receptor V1

78 *DNAH5*: dynein, axonemal, heavy chain 5

79 SNP: single nucleotide polymorphism

80 GWAS: genome-wide association study

81 SPT: skin prick test

82 EGEA: Epidemiological study on the Genetics and Environment of Asthma

83 SLSJ: Saguenay-Lac-Saint-Jean study

84 MRCA: Medical Research Council funded collection of nuclear families with Asthma

85 MRCE: Medical Research Council funded collection of nuclear families with Eczema

- 86 GRAIL: Gene Relationships Across Implicated Loci
- 87 QC: quality control
- 88 MAF: minor allele frequency
- 89 PCs: principal components
- 90 LD: linkage disequilibrium
- 91 ORs: odds-ratios
- 92 GTEx: Genotype-Tissue Expression
- 93 ETS: environmental tobacco smoke
- 94 CI: confidence interval
- 95

96 **INTRODUCTION**

97 Allergies and asthma are among the most common diseases in industrialized countries. Although
98 environmental factors play an important role in allergic diseases, estimates of heritability of allergy,
99 which range between 25% and 80%, suggest significant genetic contribution.¹ Genome-wide
100 association studies (GWAS) have identified a number of loci associated with allergic diseases (i.e.,
101 asthma, atopic dermatitis, rhinitis),^{2,3} but these loci only explain a small part of the genetic risk.
102 Part of the difficulty encountered in identifying the genetic factors involved in these allergic
103 diseases is due to the heterogeneity of these diseases and the uncertainty of diagnosis. However,
104 this problem can be alleviated by the study of an endotype underlying allergic diseases, such as
105 allergic sensitization or atopy.

106 Atopy is characterized by the production of allergen-specific immunoglobulin E against
107 environmental allergens. Estimates of heritability of atopy range from 40% to 85%.^{4,5} Many
108 candidate genetic studies of atopy have been conducted but have often led to inconsistent results.⁶
109 While the first GWAS of allergic sensitization only reported a few loci,⁷⁻¹⁰ two recent large-scale
110 meta-analyses of allergic sensitization¹¹ and self-reported allergy¹² increased the number of
111 associated loci to 10 and 16 loci, respectively. However, other loci may influence atopy as it is well
112 known that GWAS alone cannot reveal the whole genetic landscape underlying complex
113 phenotypes.

114 Heterogeneity across studies, which may be caused by variability in the genetic background of the
115 populations, environmental exposures, or study design, may be a limitation of meta-analyses of
116 GWAS for identifying new loci associated with a trait. Notably, the importance of data sampling
117 was recently highlighted by a positional cloning study of eczema, where association with
118 *ANO3/MUC15* genetic variants was only found in family samples ascertained through asthmatic

119 subjects but neither in families ascertained through eczema patients nor in a case/control study of
120 eczema.¹³

121 Another limitation of GWAS is that they typically focus on the analysis of individual single
122 nucleotide polymorphisms (SNPs) and are underpowered to detect genetic factors which have a
123 small marginal effect but rather interact with each other. Gene-gene interaction analysis (or
124 epistasis analysis) has the ability to reveal novel genes involved in complex traits but raises an
125 enormous multiple-testing problem when performed at the genome-wide level. Statistical and
126 biological filtering pipelines can be used to limit the search for SNP-SNP interactions.¹⁴ Following
127 the “guilt-by-association” assumption which states connected genes are usually participating in the
128 same or related cellular functions,¹⁵ search for interactions can be restricted to genes pointed out
129 by a preliminary GWAS (e.g., interactions of genes harboring significant association signals with
130 genes harboring suggestive associations) and showing relationships based on prior knowledge. One
131 knowledge-based approach that can be particularly useful to prioritize genes for epistasis analysis
132 is text-mining of the literature as it can highlight relationships between genes¹⁶ according to their
133 co-occurrence with the same words in scientific articles.

134
135 The objective of this study was to identify novel genetic factors influencing atopy by combining a
136 GWAS and epistasis analysis driven by statistical and knowledge-based evidence in three family
137 samples ascertained through asthmatic subjects: the French Epidemiological study on the Genetics
138 and Environment of Asthma (EGEA; 1,660 subjects), the French-Canadian Saguenay-Lac-Saint-
139 Jean study (SLSJ; 1,138 subjects) and the Medical Research Council UK study (MRC; 446
140 subjects). Our overall analysis strategy included three main steps: (1) a genome-wide single-SNP
141 association analysis, (2) the selection of related gene pairs based on statistical filtering from GWAS

142 results and text-mining filtering using the Gene Relationships Across Implicated Loci (GRAIL)
143 approach,¹⁷ and (3) a SNP-SNP interaction analysis for the selected gene pairs.

144

145 **MATERIALS AND METHODS**

146 *Study datasets and definition of atopy*

147 The EGEA study combines a case-control and a family-based study of asthma. The whole study
148 population includes 388 families ascertained through at least one asthmatic proband recruited in
149 chest clinics (1,705 probands and first-degree relatives) plus 415 population-based controls (total
150 of 2,120 subjects). All subjects were born in France and were of European ancestry. The protocol
151 of this study has been described elsewhere.¹⁸⁻²⁰ Atopy was assessed by skin prick tests (SPT)
152 performed in 1,978 subjects. A positive SPT response was defined as a wheal diameter \geq 3mm to
153 at least one of 11 aeroallergens belonging to three groups (indoor allergens, outdoor allergens,
154 molds). After quality control (QC) of genotypic data, 925 atopic and 735 non-atopic subjects were
155 included in the analysis.

156 The Saguenay-Lac-Saint-Jean and Quebec City Familial Asthma Collection (SLSJ) consists of a
157 French-Canadian founder population panel of 253 multigenerational families from Saguenay-Lac-
158 Saint-Jean region, ascertained through two asthmatic probands.²¹ This study has been described
159 elsewhere.²¹ Skin tests were done in 1,195 SLSJ subjects and atopy was defined similarly as in
160 EGEA. After QC of genotypic data, the analysis dataset included 641 atopic and 497 non-atopic
161 subjects.

162 The Medical Research Council (MRC) UK study includes 207 nuclear families, recruited through
163 at least one proband with childhood-onset asthma (MRCA sample). The study protocol has been
164 described elsewhere.²² Atopy was defined similarly as in EGEA. To increase the number of
165 unaffected subjects (controls), we included subjects from another MRC-UK dataset that were

166 recruited through probands with eczema (MRCE sample). Only subjects without asthma, without
167 eczema and with low IgE levels were used as controls in this study. We checked that the age and
168 gender distributions were similar in MRCA and MRCE samples. After QC of genotypic data, the
169 analysis sample included 106 atopic and 340 non-atopic subjects. The whole UK sample will be
170 subsequently designated as the MRC sample.

171 Protocols of EGEA, SLSJ and MRC studies have been approved by the local ethical committees.
172 All adult participants and child's legal guardians provided written informed consent.

173

174 ***Genotyping***

175 Both EGEA and SLSJ datasets were genotyped using the Illumina 610-Quad array (Illumina, San
176 Diego, CA), as part as of the Gabriel asthma consortium GWAS.²³ Stringent quality criteria were
177 applied to select both individuals and SNPs and have been previously detailed.^{23,24} After QC, there
178 was a final set of 501,167 autosomal SNPs for analysis. The offspring in MRCA families and
179 MRCE controls were genotyped using the Illumina Sentrix HumanHap300 BeadChip (307,981
180 autosomal SNPs), as part of the first asthma GWAS.^{22,23} QC for MRC samples has been detailed
181 elsewhere.^{22,25} In order to get a number of SNPs in MRC sample as large as in EGEA and SLSJ
182 samples, SNP imputation was performed using MACH v1.00 software²⁶ and HapMap2 release 21
183 CEU haplotypes as reference panel. Imputed SNPs were kept for analysis if their imputation quality
184 score (rsq)²⁷ was ≥ 0.5 and minor allele frequency was $\geq 5\%$.

185

186 ***Descriptive statistics and strategy of analysis***

187 Descriptive statistics of atopy together with sex, age and asthma status were assessed in each
188 dataset using Stata® V14.1 (distributed by Stata Corporation, College Station, Texas, USA). The

189 workflow of our three-step analysis strategy is summarized in Figure 1 and presented in the
190 following paragraphs.

191

192 ***Genome-wide single-SNP analysis***

193 We performed a two-stage GWAS. In the first stage, association analysis between individual SNPs
194 and atopy was carried out in the EGEA dataset. This analysis was based on a logistic regression
195 model assuming an additive model for SNP effect, using Stata® V14.1. This model was adjusted
196 for significant effects of age and sex and two principal components (PCs) to account for population
197 structure. We took into account familial dependencies using the cluster and robust options of the
198 logit function in Stata®. Test of SNP effect was based on a Wald-test. In a second stage, the SNPs
199 reaching $P \leq 10^{-4}$ in EGEA were followed-up in SLSJ and MRC. The association analysis in SLSJ
200 and in MRC used the same model as in EGEA. The results of stage 2 datasets and, then, of the
201 three datasets were combined using a fixed-effects meta-analysis. SNPs were declared significantly
202 associated with atopy if the three datasets meta-analysis P -value (P_{meta}) reached the genome-wide
203 significance level of 1.5×10^{-7} . This threshold was obtained by dividing the type I error of 5% by
204 the effective number of independent SNPs in the Illumina 610-Quad array.²⁸

205

206 ***Selection of gene pairs using both statistical and text-mining filters***

207 The statistical filtering consisted of selecting two sets of genes using the GWAS results: genes
208 showing significant association with atopy (set-1) and genes showing suggestive association with
209 atopy (set-2). The set-1 included all genes lying at a distance of 50 kb or less from SNPs reaching
210 the genome-wide significance level in the GWAS meta-analysis. The set-2 included all genes that
211 were at most 50 kb apart from SNPs having $P \leq 10^{-4}$ in the stage 1 EGEA dataset and were not part

212 of set-1. To assign SNPs to genes, we used NCBI dbSNP Build 137 and human Genome Build
213 37.3. We further filtered gene pairs (formed by crossing set-1 genes with set-2 genes) through
214 GRAIL¹⁷ text-mining of PubMed abstracts (available in October 2014). For each gene, GRAIL
215 builds a vector of words where the elements of this vector are weights that take values between 0
216 and 1 depending on how often a word is found with a gene in an abstract. Then, GRAIL computes
217 pairwise similarity between genes from gene/word vectors and ranks the similarities between each
218 gene from set-1 and all genes of the genome. The P_{GRAIL} of a gene from set-2 with a gene from set-
219 1 is equal to the proportion of all genes that have similarity with the set-1 gene greater than the
220 similarity between set-2 and set-1 genes (i.e. rank divided by total number of genes across the
221 genome). We used the threshold of $P_{\text{GRAIL}} \leq 0.10$, as recommended,¹⁷ to select related gene pairs
222 for further epistasis analysis.

223

224 *SNP-SNP interaction analysis for selected gene pairs*

225 As for the single-SNP association analysis, we performed a two-stage SNP-SNP interaction
226 analysis. At stage 1, we analyzed all SNP-SNP interactions for the GRAIL-selected gene pairs in
227 the EGEA dataset. For each gene, we considered all SNPs lying within gene boundaries. Pairwise
228 SNP-SNP interactions were evaluated by logistic regression assuming an additive model for SNP
229 main effects and interaction and adjusting for the same covariates (age, sex, PCs) as in the GWAS,
230 using Stata® V14.1. We used the same coding scheme as usually proposed for SNP-SNP
231 interaction modelling.²⁹ We modeled the additive effect of a SNP by coding the genotypes of
232 homozygotes for the minor allele, heterozygotes and homozygotes for the major allele as 1, 0, and
233 -1; the interaction term between two SNPs was obtained by multiplication of these genotypic values
234 for the two SNPs. Test of interaction was based on a likelihood-ratio test which follows a Chi-
235 square distribution with one degree of freedom. We discarded all SNP pairs for which one or more

236 of the nine genotypic combinations appeared in fewer than five subjects (cases or controls). In a
237 second stage, all SNP pairs showing suggestive evidence for interaction in EGEA ($P_{\text{int}} \leq 5 \times 10^{-3}$)
238 were followed-up in SLSJ and MRC. The results of the stage 2 datasets and, then, of the three
239 datasets were meta-analyzed using a fixed-effects model.

240 To correct for multiple testing, we computed, for each gene pair investigated, the effective number
241 of independent interaction tests from the eigenvalues of the correlation matrix of products of SNP
242 variables, using an extension of Li and Ji's method.³⁰ The corrected threshold to declare an
243 interaction statistically significant was equal to the 5% type I error divided by the sum of effective
244 number of independent interaction tests over all gene pairs tested.

245

246 **Stratified analyses according to asthma status**

247 Because family samples were ascertained through asthmatic probands, we investigated whether
248 SNP associations and SNP-SNP interactions detected with atopy might be related to the presence
249 of asthma. Single-SNP and SNP-SNP interaction analyses were repeated in the two groups of
250 asthmatic and non-asthmatic subjects separately. These analyses were performed for the SNPs that
251 showed significant results in the meta-analyses of the three datasets. Homogeneity of the odds-
252 ratios (ORs) between the two groups was tested using the Cochran's Q statistic.³¹

253

254

255 **RESULTS**

256 *Descriptive statistics*

257 A total of 1,660 EGEA, 1,138 SLSJ and 446 MRC subjects were included in this study. The
258 proportion of atopic subjects was similar in EGEA and SLSJ (55.7% and 56.3% respectively) but
259 was lower in MRC (23.8%; $P \leq 10^{-3}$). In each study, there was a higher proportion of males in atopic

260 than in non-atopic subjects and atopic subjects were younger than non-atopic subjects (see Table
261 E1 in the Online Repository). As expected, the proportion of asthmatic subjects was higher in
262 atopic than in non-atopic subjects in all datasets (Table E1). In EGEA (respectively in SLSJ and
263 MRC), 78.0% (75.0% and 78.3%) of atopic subjects had positive SPT to indoor allergens, 55.5%
264 (77.5% and 52.8%) to outdoor allergens, and 34.8% (14.8% and 12.3%) to molds.

265

266 ***Genome-wide single-SNP analysis***

267 In the stage 1 EGEA dataset, no SNP reached the genome-wide significance level of 1.5×10^{-7} (see
268 quantile-quantile (QQ) plot and Manhattan plot in Figures E1 and E2). However, 73 SNPs lying in
269 47 loci showed associations with atopy exceeding the screening threshold of $P \leq 10^{-4}$. These SNPs
270 were followed-up in the stage 2 SLSJ and MRC datasets and meta-analyzed (Table E2). The SNP
271 rs4916831 within *ADGRV1* gene at 5q14 reached the genome-wide significance level
272 ($P_{\text{meta}} = 6.8 \times 10^{-9}$) in the overall meta-analysis of the three datasets (Table I). Four other SNPs at that
273 locus, in moderate linkage disequilibrium (LD) with rs4916831 (r^2 ranging between 0.51 and 0.79),
274 showed suggestive association ($4.3 \times 10^{-7} \leq P_{\text{meta}} \leq 3.8 \times 10^{-6}$; Table I).

275

276 ***Selection of gene pairs using both statistical and text-mining filters***

277 The gene set-1 included *ADGRV1*, the only gene significantly associated with atopy. There were
278 30 genes that lied fewer than 50 kb apart from the 65 SNPs at 46 loci having $P \leq 10^{-4}$ in EGEA (after
279 exclusion of *ADGRV1* SNPs) and formed gene set-2 (Table E3). When GRAIL was applied to 30
280 gene pairs (date accessed: 04/24/2015), formed by each of these 30 genes with *ADGRV1*, three
281 genes were related with *ADGRV1* at $P_{\text{GRAIL}} < 0.10$: *DNAH5* on 5p15 ($P_{\text{GRAIL}} = 0.084$), *CHD7* on 8q12
282 ($P_{\text{GRAIL}} = 3.2 \times 10^{-3}$) and *ATP8B1* on 18q21 ($P_{\text{GRAIL}} = 0.016$).

283

284 ***SNP-SNP interaction analysis for selected gene pairs***

285 In the stage 1 EGEA dataset, the three GRAIL-selected gene-pairs (*ADGRVI/DNAH5*,
286 *ADGRVI/CHD7*, *ADGRVI/ATP8B1*) were each examined for SNP-SNP interactions, making a
287 total of 5,324 SNP pairs. There were 37 SNP pairs that reached $P_{\text{int}} \leq 5 \times 10^{-3}$ in EGEA and were
288 followed-up in SLSJ and MRC at stage 2. Two of these SNPs pairs, which are related to the
289 *ADGRVI* and *DNAH5* gene pair, met the multiple-testing corrected threshold, estimated to be
290 7.3×10^{-5} (see Table E4), in the meta-analysis of the three datasets (Table II). The two significant
291 interactions involved the same SNP rs17554723 within *ADGRVI* and two SNPs within *DNAH5*,
292 rs2134256 ($P_{\text{meta-int}} = 3.6 \times 10^{-5}$) and rs1354187 ($P_{\text{meta-int}} = 6.1 \times 10^{-5}$), that are in moderate LD ($r^2 = 0.50$;
293 $D' = 0.95$). However, further conditional regression analysis in each of the strata defined by
294 genotypes at *ADGRVI* rs17554723 showed that *DNAH5* rs1354187 was no longer significantly
295 associated with atopy ($P \geq 0.15$) when conditioning on *DNAH5* rs2134256. The most significant
296 SNP pair shows a pattern of interaction in which the ORs for atopy associated with TT (or CC)
297 genotype at *DNAH5* rs2134256 are in opposite direction according to the genotype, AA (or GG),
298 at *ADGRVI* rs17554723 (Figure 2). This pattern was consistent in all three datasets (Figure 2).

299

300 **Stratified analyses according to asthma status**

301 Association analyses of atopy with the genome-wide significant *ADGRVI* rs4916831 SNP in
302 asthmatic and non-asthmatic subjects did not show any relationship with presence of asthma in the
303 stage 1 and stage 2 datasets and meta-analysis of the three datasets (P_{Cochran} for test of homogeneity
304 between the two groups ≥ 0.82 ; Table E5A). In the meta-analysis, the evidence for association was
305 even stronger although not significantly in non-asthmatics ($P = 7.8 \times 10^{-6}$) than in asthmatics
306 ($P = 1.4 \times 10^{-4}$). Similarly, interaction analyses for *ADGRVI* and *DNAH5* SNPs did not show any
307 relationship with asthma ($P_{\text{Cochran}} \geq 0.30$; Table E5B). The evidence for interaction was only

308 significant in non-asthmatic subjects (Table E6B); this can be at least partly explained by the larger
309 sample size of non-asthmatic (N=1,849) than asthmatic subjects (N=1,354).

310

311 **Functional annotations of SNPs showing significant results**

312 All SNPs that show significant association (or interaction) with atopy are intronic. The two
313 *ADGRV1* SNPs, rs4916831 and rs17554723 on 5q14, detected through GWAS and interaction
314 analysis, lie 120 kb apart in introns 83 (rs4916831) and 70 (rs17554723) and are in low LD
315 ($r^2=0.20$, $D'=0.75$). The two *DNAH5* SNPs (rs2134256 and rs1354187) at 5p15.2 are located in
316 introns 58 and 60 (8 kb apart) but only rs2134256 accounts for the interaction signal (see above).
317 By interrogating the Genotype-Tissue Expression (GTEx) database,³² rs4916831 was found
318 associated with *ADGRV1* expression in esophagus mucosa ($P=7.5 \times 10^{-7}$).³² We also investigated
319 whether the *ADGRV1* and *DNAH5* SNPs (as well as their proxies, $r^2 \geq 0.80$) map to functionally
320 important regulatory regions using HaploRegV4.³³ As shown in Table E6, these SNPs and/or
321 proxies map to binding sites of various transcription factors (TFs). In addition, four proxies of
322 *ADGRV1* rs4916831 map to enhancer histone marks in lung and skin while a proxy of *DNAH5*
323 rs2134256 maps to promoter and enhancer marks in hematopoietic stem cells.

324

325 **DISCUSSION**

326 By combining genome-wide single-SNP analysis and epistasis analysis driven by statistical and
327 knowledge-based evidence in three asthma-ascertained family datasets, we identified significant
328 association of atopy at a novel 5q14 locus harboring *ADGRV1* gene and significant interaction
329 between *ADGRV1* and *DNAH5* genetic variants.

330 The interaction between *ADGRV1* and *DNAH5* variants has biological relevance as these two genes
331 are both involved in ciliopathies and ciliary function. Ciliopathies comprise a group of disorders

332 associated with genetic mutations encoding defective proteins, which result in either abnormal
333 formation or function of cilia.³⁴ Mutations in the adhesion G protein-coupled receptor V1
334 (*ADGRV1*) gene cause Usher syndrome type IIC, a ciliopathy characterized by hearing loss and
335 visual impairment,^{35,36} while mutations of dynein axonemal heavy chain 5 (*DNAH5*) gene cause
336 primary ciliary dyskinesia type 3, a ciliopathy which combines upper and lower tract respiratory
337 manifestations, male infertility, and situs inversus.³⁷ The ADGRV1 protein (also called GPR98) is
338 a component of the Usher protein network that functions in stereocilia of inner ear hair cells and
339 photoreceptor cilia. The heavy chain of axonemal dynein, encoded by *DNAH5*, is part of a
340 microtubule-associated motor protein complex that is responsible for cilia mobility, especially in
341 respiratory epithelial cells where cilia motility is essential for mucus transport and airway
342 clearance.³⁸ Although the respective function of ADGRV1 and *DNAH5* proteins was initially
343 described in different organs, these proteins may also have related functions. Indeed, the cilium in
344 photoreceptors is ultrastructurally very similar to the nasal ciliated epithelium and the nasal ciliated
345 epithelium of Usher syndrome II patients was found to have a lower ciliary beat frequency than
346 healthy controls.³⁹ Moreover, Usher syndrome has been reported to be associated with
347 bronchiectasis, sinusitis and reduced nasal mucociliary clearance.⁴⁰

348 Besides the involvement of both ADGRV1 and *DNAH5* proteins in cilia functions, which supports
349 the statistical interaction found between these two genes, both *DNAH5* and *ADGRV1* genes have
350 been previously associated with respiratory diseases and related phenotypes. Recent GWAS
351 reported significant association of *DNAH5* variants with total lung capacity in chronic obstructive
352 pulmonary disease⁴¹ and suggestive association with Immunoglobuline E grass sensitization.⁹
353 However, the SNP reported by that latter study was not in LD with the *DNAH5* SNPs interacting
354 with *ADGRV1* SNP in this study ($r^2 < 0.13$). Based on an approach similar to ours, which combined
355 genome-wide expression data in nasal epithelial cells, allele frequency variation between

356 populations and literature search to select candidate genes, nominal association of asthma with
357 *DNAH5* was reported and stronger association was found with *KIF3*, a gene involved in transport
358 of protein complexes within cilia and potentially in allergen clearance as *DNAH5*.⁴² In addition,
359 *DNAH5* belongs to the same gene family as *DNAH9* which showed interaction with environmental
360 tobacco smoke (ETS) exposure for bronchial hyperresponsiveness in EGEA and SLSJ families.⁴³
361 Moreover, suggestive association of *ADGRV1* with asthma has been recently reported by a meta-
362 analysis of GWAS.⁴⁴ Though most previously reported associations concern asthma or respiratory
363 phenotypes, the interaction between *ADGRV1* and *DNAH5* SNPs associated with atopy in the
364 present study appears independent of asthma, as shown by the stratified analysis on asthma.
365 Although the mechanism by which these two genes influence atopy is still unknown, we can
366 hypothesize that they are involved in dysfunction of cilia that move secreted mucus containing
367 trapped foreign particles up and out of the airways, which favors allergic sensitization. This is
368 supported by recent observations of a differential mRNA expression of both *ADGRV1* and *DNAH5*
369 genes in sputum from House Dust Mite (HDM)-sensitized wheezing subjects as compared to non-
370 atopic controls.⁴⁵ Furthermore, *DNAH5* as well as other genes of the same family including *DNAH9*
371 were among the highest-ranking co-expression hubs in one of the HDM-wheezing associated gene
372 modules, which was strongly enriched with genes involved in the function of ciliated epithelial
373 cells.⁴⁵ All these observations suggest cilia-related genes may constitute an important emerging
374 pathway for atopy.

375 The strategy used in this study, that enabled identifying novel relevant candidates for atopy,
376 combined genome-wide single-SNP analysis and gene-gene interaction analysis based on both
377 statistical filtering of GWAS results and text-mining filtering. It is of note that our three-step
378 strategy was designed *a priori* and SNP-SNP interaction tests were only performed for gene pairs
379 selected through our two filtering processes. The genome-wide single-SNP analysis pointed

380 towards one gene (*ADGRVI*) which harbored the lead SNP rs4916831 reaching genome-wide
381 significance and four other SNPs showing suggestive association. By increasing the density of
382 SNPs through Hapmap2-based imputation at that locus, an additional SNP ($r^2=0.80$ with
383 rs4916831) reached genome-wide significance and six other SNPs had P-values within one order
384 of magnitude of the genome-wide threshold (results not shown), which strengthens our finding.
385 Further conditional analysis in that region showed that association with atopy was only accounted
386 for by the lead genotyped SNP. The subsequent statistical and text-mining filters, used prior to
387 epistasis analysis, made it possible to detect gene-gene interaction by lowering the multiple testing
388 burden. Indeed, use of both filters reduced the number of interaction tests by 9-fold as compared
389 to using the statistical filter only. The text-mining filter was based on GRAIL that was shown to be
390 successful in pointing out true disease regions that were validated.¹⁷ Although many sources of
391 biological information can be used to connect genes, such as co-expression gene networks or
392 protein-protein interaction networks, the advantage of GRAIL is to provide a broader framework
393 for revealing gene-gene relationships of any origin through literature search. However, GWAS and
394 candidate gene studies, which are driven by researchers' expectations, can create a bias towards
395 genes that are frequently reported in the literature. An appropriate approach would be to utilize the
396 existing knowledge and to correct for potential bias but, to our knowledge, such method does not
397 exist yet.

398

399 In conclusion, this study shows that the proposed strategy that combines GWAS and epistasis
400 analysis driven by statistical and knowledge-based evidence can successfully identify strong
401 candidate genes for complex phenotypes as atopy. The interaction between *DNAH5* and *ADGRVI*,
402 two genes involved in cilia functions, is of biological relevance and provides a novel mechanism

403 underlying atopy. Further studies, including functional and experimental studies, are needed to
404 confirm the current findings and to identify the functional variants.

405

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443

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- 553

Table I. *ADGRVI* locus on 5q14 showing significant association with atopy

| SNP | Position (kb)* | Alleles† | MAF‡ | Stage 1 | | Stage 2 | | | | | | Overall Meta-Analysis | | |
|------------|----------------|----------|------|----------------|----------------------|----------------|----------------------|--------------|----------|---------------|-------------------------------|-----------------------|-----------------------------|--------------------------------|
| | | | | EGEA (N=1,660) | | SLSJ (N=1,138) | | MRC (N=446) | | Meta-Analysis | | beta (se) § | <i>P</i> _{meta} †† | <i>P</i> _{Cochran} ‡‡ |
| | | | | beta (se) § | <i>P</i> | beta (se) § | <i>P</i> | beta (se) § | <i>P</i> | beta (se) § | <i>P</i> _{stage2} ** | | | |
| rs4244205 | 90,188 | A/G | 0.41 | -0.35 (0.08) | 1.1x10 ⁻⁵ | -0.19 (0.10) | 6.0x10 ⁻² | -0.14 (0.18) | 0.45 | -0.18 (0.09) | 4.4x10 ⁻² | -0.27 (0.06) | 3.8x10 ⁻⁶ | 0.35 |
| rs4916831 | 90,212 | A/G | 0.44 | -0.40 (0.08) | 1.0x10 ⁻⁶ | -0.32 (0.11) | 2.3x10 ⁻³ | -0.21 (0.17) | 0.23 | -0.29 (0.09) | 1.2x10 ⁻³ | -0.35 (0.06) | 6.8x10⁻⁹ | 0.59 |
| rs10060641 | 90,213 | T/C | 0.38 | -0.39 (0.08) | 7.2x10 ⁻⁷ | -0.17 (0.11) | 0.11 | -0.24 (0.19) | 0.22 | -0.18 (0.09) | 4.8x10 ⁻² | -0.30 (0.06) | 4.3x10 ⁻⁷ | 0.23 |
| rs12054681 | 90,217 | C/A | 0.37 | -0.39 (0.08) | 9.7x10 ⁻⁷ | -0.14 (0.11) | 0.18 | -0.29 (0.21) | 0.16 | -0.17 (0.09) | 6.5x10 ⁻² | -0.30 (0.06) | 7.8x10 ⁻⁷ | 0.18 |
| rs949787 | 90,251 | G/T | 0.28 | -0.33 (0.08) | 5.5x10 ⁻⁵ | -0.23 (0.10) | 2.0x10 ⁻² | -0.19 (0.20) | 0.36 | -0.22 (0.09) | 1.2x10 ⁻² | -0.28 (0.06) | 3.2x10 ⁻⁶ | 0.65 |

*Position in kilobases (kb) according to NCBI dbSNP Build 137

†Major allele/Minor allele

‡Minor allele frequency

§beta is the regression coefficient for a one-unit increase of the effect allele in logistic regression assuming an additive model; se is the standard error associated with the regression coefficient.

||*P* is the *P*-value associated with the Wald test of SNP effect.

***P*_{stage2} is the *P*-values associated with the Wald test of meta-analyzed SNP effect in the stage 2 datasets (SLSJ and MRC).

††*P*_{meta} is the *P*-value associated with the Wald test of meta-analyzed SNP effect in the three datasets (EGEA, SLSJ, MRC); the *P*-value is shown in bold when it reached the multiple-testing corrected threshold of 1.5x10⁻⁷.

‡‡*P*_{Cochran} is the *P*-value associated with Cochran's Q test of homogeneity across the three datasets.

Table II. SNP pairs showing significant interaction for atopy

| SNPs | Chr* | Genes† | Alleles‡ | MAF§ | Stage 1 | | | Stage 2 | | | | | | Overall Meta-analysis | | | | | | |
|-------------|------|---------------|----------|------|----------------|--------------|----------------------|----------------|--------------|----------------------|-------------|--------------|----------------|-----------------------|--------------|-----------------------------------|--------------|--------------|--|----------------------|
| | | | | | EGEA (N=1,660) | | | SLSJ (N=1,138) | | | MRC (N=446) | | | Meta-Analysis | | | Main effect | | Interaction | |
| | | | | | Main effect | Interaction | | Main effect | Interaction | | Main effect | Interaction | | Main effect | Interaction | | Main effect | Interaction | | |
| | | | | | beta (se)¶ | beta (se)¶ | P_{int}^{**} | beta (se)¶ | beta (se)¶ | P_{int}^{**} | beta (se)¶ | beta (se)¶ | P_{int}^{**} | beta (se)¶ | beta (se)¶ | $P_{stage2-int}^{\dagger\dagger}$ | beta (se)¶ | beta (se)¶ | $P_{meta-int}^{\dagger\dagger}$ | $P_{Cochran}^{\S\S}$ |
| rs17554723 | 5 | <i>ADGRV1</i> | A/G | 0.33 | -0.06 (0.10) | -0.38 (0.12) | 3.0×10^{-3} | 0.02 (0.13) | -0.42 (0.16) | 1.1×10^{-2} | 0.13 (0.23) | -0.28 (0.33) | 0.40 | 0.04 (0.11) | -0.39 (0.14) | 6.1×10^{-3} | -0.02 (0.08) | -0.38 (0.09) | 3.6×10^{-5} | 0.84 |
| rs2134256¶¶ | 5 | <i>DNAH5</i> | T/C | 0.25 | 0.13 (0.09) | | | -0.06 (0.13) | | | 0.03 (0.26) | | | -0.04 (0.12) | | | 0.06 (0.07) | | | |
| rs17554723 | 5 | <i>ADGRV1</i> | A/G | 0.33 | 0.03 (0.09) | -0.34 (0.11) | 3.3×10^{-3} | 0.13 (0.11) | -0.35 (0.14) | 1.4×10^{-2} | 0.19 (0.21) | -0.16 (0.29) | 0.59 | 0.14 (0.10) | -0.32 (0.12) | 9.3×10^{-3} | 0.08 (0.06) | -0.33 (0.08) | 6.1×10^{-5} | 0.92 |
| rs1354187¶¶ | 5 | <i>DNAH5</i> | T/C | 0.36 | 0.08 (0.08) | | | -0.04 (0.11) | | | 0.05 (0.22) | | | -0.02 (0.10) | | | 0.04 (0.06) | | | |

*Chr is the chromosome number where the SNP is located

†Gene symbol of gene where SNP lies

‡Major allele/Minor allele

§Minor allele frequency

¶beta for the main effect is the regression coefficient for a one-unit increase of the effect allele in logistic regression assuming an additive model; beta for interaction is the regression coefficient for homozygotes for the minor allele at the two loci or homozygotes for the major allele at the two loci with respect to heterozygotes at either one or the two loci using the coding scheme under an additive genetic model described in the methods section; se is the standard error associated with the regression coefficient.

** P_{int} is the P -value of the likelihood-ratio test for interaction between SNPs (which follows a chi-square distribution with one degree of freedom assuming an additive model).

†† $P_{stage2-int}$ is the P -values associated with the Wald test of meta-analyzed interaction effect in the stage 2 datasets (SLSJ and MRC).

††† $P_{meta-int}$ is the P -values associated with the Wald test of meta-analyzed interaction effect in the three datasets (EGEA, SLSJ, MRC); $P_{meta-int}$ is shown in bold when it reached the multiple-testing corrected threshold of 7.3×10^{-5} .

§§§ $P_{Cochran}$ is the P -value associated with Cochran's Q test of homogeneity across the three datasets.

¶¶The two *DNAH5* SNPs, rs1354187 and rs2134256, showing significant interaction with *ADGRV1* SNP are in moderate linkage disequilibrium ($r^2=0.50$; $D'=0.95$).

FIGURE LEGENDS

Figure 1. Three-step analysis strategy

Figure 2. Odds-ratio (ORs) and 95% confidence intervals for atopy associated with each genotype at *DNAH5* rs2134256 (TT, CT, CC) in each of the strata defined by genotypes at *ADGRV1* rs17554723 (AA, AG, or GG). These ORs were calculated using the genotype coding scheme defined in the text and are shown for each of the three datasets (EGEA, SLSJ, MRC) and for the combined dataset.

Figure 1.

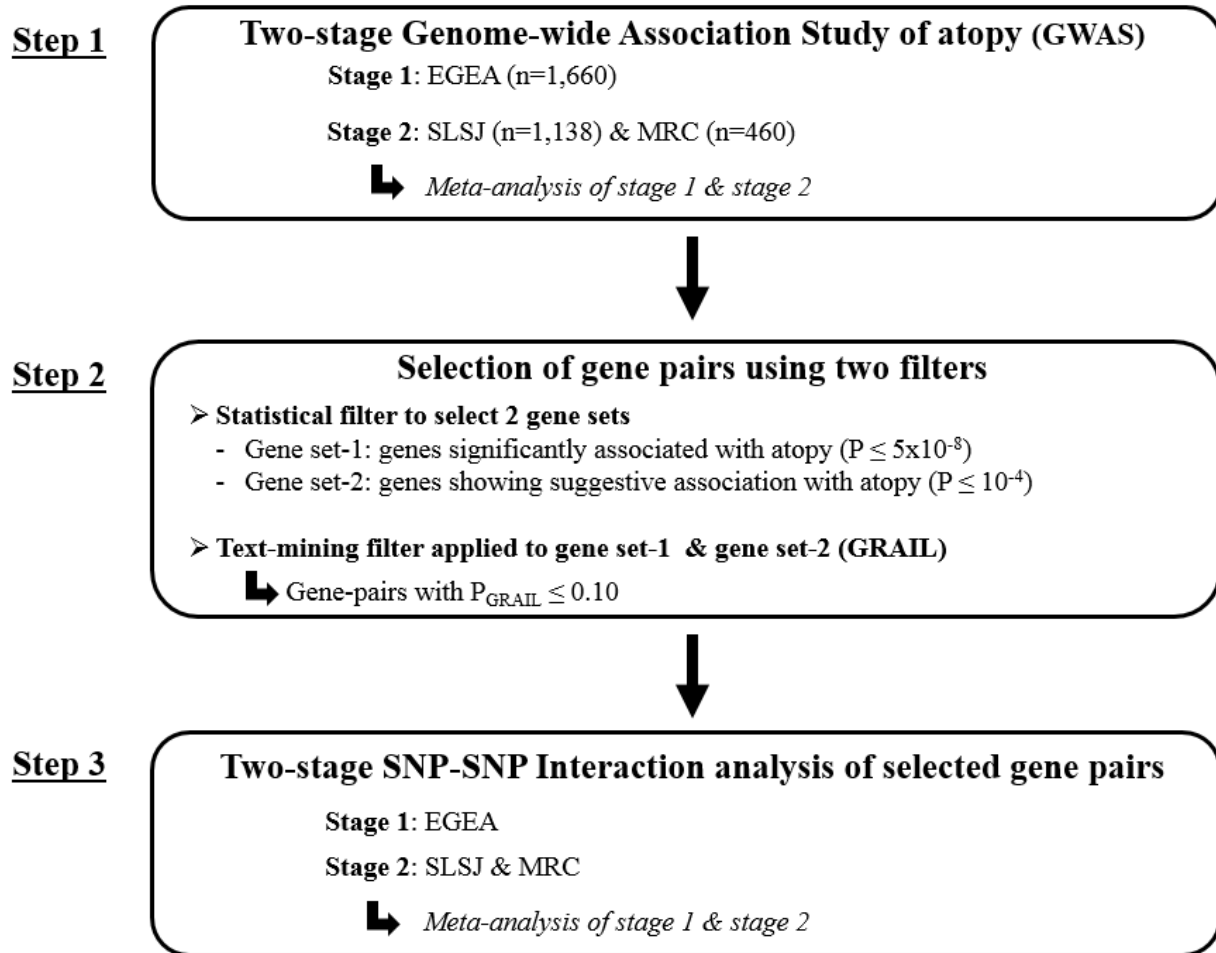


Figure 2.

