Two Loci on Chromosome 5 Are Associated with Serum IgE Levels in Labrador Retrievers

Marta Owczarek-Lipska1,2, Béatrice Lauber2,3, Vivianne Molitor2,4, Sabrina Meury2,5, Marcin Kierczak6, Katarina Tengvall7, Matthew T. Webster7, Vidhya Jagannathan1, Yvette Schlotté8, Ton Willemse8, Anke Hendricks9, Kerstin Bergvall10, Åke Hedhammar10, Göran Andersson6, Kerstin Lindblad-Toh7, Claude Favrot2,5, Petra Roosje2,4, Eliane Marti2,3, Tosso Leeb1,2*

1 Institute of Genetics, Vetsuisse Faculty, University of Bern, Bern, Switzerland, 2 DermFocus, Vetsuisse Faculty, University of Bern, Bern, Switzerland, 3 Department of Clinical Research and Veterinary Public Health, Vetsuisse Faculty, University of Bern, Bern, Switzerland, 4 Department of Clinical Veterinary Medicine, Division of Clinical Dermatology, Vetsuisse Faculty, University of Bern, Bern, Switzerland, 5 Clinic for Small Animal Internal Medicine, Dermatology Unit, Vetsuisse Faculty, University of Zurich, Zurich, Switzerland, 6 Computational Genetics Group, Department of Clinical Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden, 7 Science for Life Laboratory, Department of Medical Biochemistry and Microbiology, Uppsala University, Uppsala, Sweden, 8 Department of Clinical Sciences of Companion Animals, Faculty of Veterinary Medicine, Utrecht University, Utrecht, The Netherlands, 9 Department of Clinical Sciences, Royal Veterinary College, London, United Kingdom, 10 Department of Clinical Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden

Abstract

Crosslinking of immunoglobulin E antibodies (IgE) bound at the surface of mast cells and subsequent mediator release is considered the most important trigger for allergic reactions. Therefore, the genetic control of IgE levels is studied in the context of allergic diseases, such as asthma, atopic rhinitis, or atopic dermatitis (AD). We performed genome-wide association studies in 161 Labrador Retriever puppies with regard to total and allergen-specific immunoglobulin E (IgE) levels. We identified a genome-wide significant association on CFA 5 with the antigen-specific IgE responsiveness to *Acarus siro*. We detected a second genome-wide significant association with respect to the antigen-specific IgE responsiveness to *Tyrophagus putrescentiae* at a different locus on chromosome 5. *A. siro* and *T. putrescentiae* both belong to the family Acaridae and represent so-called storage or mite antigens. These mite antigens are considered major allergens in canine AD. No obvious candidate gene for the regulation of IgE levels is located under the two association signals. Therefore our studies offer a chance of identifying a novel mechanism controlling the host’s IgE response.


Editor: Shree Ram Singh, National Cancer Institute, United States of America

Received February 10, 2012; Accepted May 16, 2012; Published June 15, 2012

Copyright: © 2012 Owczarek-Lipska et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: This work was funded thanks to grants from the European Commission (LUPA, GA-201370) and the Albert-Heim Foundation. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: tosso.leeb@vetsuisse.unibe.ch

Introduction

Immunoglobulin E (IgE) is the class of antibodies that is most frequently recognized for its role in type I hypersensitivity (allergic) reactions. In predisposed, atopic individuals IgE is produced against specific common environmental antigens. Most of the IgE is bound on the surface of mast cells through the high affinity IgE receptor (FcεRI). Cross-linking of mast-cell bound IgEs by allergens leads to the release of histamine and many other mediators, and subsequently to allergic reactions in the skin, respiratory tract, or other organs [1–3].

Total or allergen-specific IgE levels have been analyzed as correlated endophenotypes for different allergic diseases, such as asthma, atopic rhinitis, or atopic dermatitis (AD). IgE levels were analyzed instead of directly using the disease status, as they show a higher heritability than the disease status and are assumed to be less susceptible to confounding environmental factors [4,5]. The heritability of total serum IgE levels in humans was estimated to be up to 80% [6,7]. In humans, several genome-wide association studies (GWAS) were performed to search for QTL with an influence on IgE levels [5,8–10]. So far, about five IgE QTL have been identified by this approach. These loci comprise several functional candidate genes such as e.g. the gene encoding the FcεRIα subunit of the high affinity receptor for IgE (FCER1A) on HSA 1q23 or the IL13, IL4, RAD50 region of HSA 5q31 [3]. The causative mutations underlying these QTL are not yet known.

Dogs are valuable models for many human diseases and the special population structure of purebred dogs greatly facilitates the identification of genetic risk factors [11]. AD occurs in humans and dogs [12–14] and there are certain dog breeds, which are genetically predisposed to develop AD [15–18]. IgE levels in dogs are routinely analyzed to aid in the diagnosis of canine AD. In the last years, it has been recognized that total serum IgE levels do not correlate with AD status in dogs [19]. The level of total IgE in dogs is probably much more influenced by the load of endoparasites than by responses to environmental allergens [20]. However, findings of elevated allergen-specific serum IgE levels are used together with clinical criteria to diagnose canine AD. Allergen-specific serum IgE levels are thus indicative but not pathognomonic for AD as healthy dogs may also show elevated allergen-specific IgE levels [19,21].
The major recognized environmental allergens appear to be similar between humans and dogs and include house dust and storage mites, pollen, moulds, and insects [22]. In temperate climates the house dust mites of the genus *Dermatophagoides* and especially *D. farinae* are considered the most important sources of allergens in humans and dogs and several allergens have been identified on a molecular level [23]. In addition to the “true” house dust mites, most dogs are also exposed to storage or forage mites, most notably *Tyrophagus putrescentiae*, *Acarus siro*, and *Lepidoglyphus destructor*. It has been shown that such mites can be present even in un-opened bags of dry dog food. Under suitable environmental conditions up to 90% of commercial dry foods became contaminated with forage mites within a couple of weeks after opening of the bags [24]. As exposure to forage mites seems to be quite universal in human dwellings and the term “domestic mites” has been suggested for the whole group of house dust and forage mites [25].

We are currently building the LUPA cohort of Labrador Retrievers to gain a better understanding of IgE regulation and its relation to AD. We report here the results of a GWAS with respect to immunological traits in this cohort.

**Results**

We collected sera from 161 Labrador Retrievers and determined 15 immunological phenotypes consisting of *Dermatophagoides farinae* specific IgG1 and IgG4, total IgE, and 12 additional allergen-specific IgE serum levels against *Dermatophagoides farinae*, *Dermatophagoides pteronyssinus*, *Tyrophagus putrescentiae*, *Lepidoglyphus destructor*, *Acarus siro*, *Alternaria alternata*, *Cladosporium herbarum*, *Aspergillus fumigatus*, *Penicillium sp.*, cat epithelium, flea saliva, and *Blatella germanica*.

*A. siro* is a storage mite considered to be a possible source of antigens that may provoke AD. We determined the *A. siro*-specific serum IgE levels by an enzyme-linked immunosorbent assay (ELISA) and expressed them in ELISA units (EU). The measured IgE levels ranged from 0 to 3060 EU. The lower reliable detection limit for the *A. siro*-specific IgE level is 150 EU. We treated the IgE levels as a binary trait and considered dogs with more than 150 EU as IgE-responsive to *A. siro* and dogs with less than 150 EU as IgE-negative controls.

We determined the genotypes of 174,376 SNP markers in all the dogs studied. The best-associated SNP for this trait was BICF2P1022237; CFA5:g.80,037,053C>T) that was significantly associated with the *A. siro*-specific IgE response with a raw p-value of 1.07×10^-7_. Apart from these two SNPs, no other SNP on any chromosome reached genome-wide significance.

The 27 best associated markers of the GWAS were clustered on CFA 5 in an interval ranging from 79.0–86.7 Mb. Only the 28th best-associated marker resided at a different locus on CFA 37. The observed linkage disequilibrium of the association signals on CFA 5 delineates the associated interval to approximately 3.5 Mb ranging from 79.0–82.5 Mb (Figure 2).

The canine genome annotation still remains imperfect. Therefore, we extrapolated the gene content of the associated region from the orthologous human genome interval. The associated region matches to two counterparts on HSA 16, located between 70.1–74.0 Mb and 74.4–74.7 Mb, respectively (Figure 2). This region is very gene-rich and contains 69 annotated genes in the human genome (NCBI build 37.3). There is no obvious functional candidate gene known to be involved in IgE regulation in the associated interval. However, there are some genes related to the immune system, such as e.g. the interleukin 34 gene (*IL34*), in this interval.

Apart from the association to *A. siro*-specific IgE levels we also found a significantly associated SNP with respect to the allergen-specific IgE levels against *Tyrophagus putrescentiae* (Table 2). The marker BICF2P630182288 at position 33,656,088 on CFA 5 has a raw p-value of 6.10×10^-5_. This marker is 46 Mb away from the highest association to *A. siro*-specific IgE levels. Interestingly however, the region with the *T. putrescentiae*-specific IgE association also showed a moderate association with respect to *A. siro*-specific IgE levels (Table 2 and Figure 2A).

We further analyzed whether there are any correlations between the *A. siro*-specific IgE responsiveness and the other studied traits. The best-associated SNP for this trait was BICF2S2297212 (Table 1). The A-allele at this SNP had a frequency of 7.8% and occurred almost exclusively in *A. siro*-specific IgE non-responsive dogs. When we grouped the dogs according to their genotypes at the associated SNP, we observed a consistent trend for dogs with the A-allele to have lower total and lower allergen-specific IgE levels with respect to all tested allergens compared to the dogs that were homozygous G/G. The genotype at this SNP had no visible correlation with the *Dermatophagoides farinae*-specific IgG1 or IgG4 levels (Figure 3).

**Discussion**

Atopy is the predisposition to increased IgE production and immediate hypersensitivity in response to exposure to various environmental allergens [26]. Often, intradermal testing (IDT) and/or allergen-specific serological IgE tests are used to support the clinical diagnosis of canine AD. AD is a complex disease influenced by many genetic and environmental factors [16–18,27,28]. AD affected dogs are often sensitized to the common house dust mite *Dermatophagoides farinae* [29]. However, Roque et al. [30] reported controversial findings where significantly higher *Dermatophagoides farinae*-IgE levels were found in non-atopic compared to atopic dogs.

It is well known that *Dermatophagoides farinae* allergens provoke positive immunological reactions in humans and dogs [29]. It has also been reported that storage mites such as *Acarus siro*, *Glycophagus*
domesticus, Tyrophagus putrescentiae, and Lepidoglyphus destructor, which are closely related to house dust mites, are involved in sensitization and allergy induction in humans [31]. To investigate which factors influence allergen-specific IgE levels in Labrador Retrievers we performed GWAS for 12 allergen-specific IgE levels in addition to total IgE and Dermatophagoides farinae-specific IgG1, and IgG4 levels as proposed in a human AD study [32]. It has been reported that 18%–50% of atopic dogs manifest sensitization to A. siro [29,33]. We found a significant association of the IgE responsiveness to A. siro in Labradors on CFA 5. We performed the GWAS using the allergen-specific IgE levels as a binary trait and we also confirmed these results by treating the IgE levels as continuous trait (data not shown).

The locus of the A. siro IgE-responsiveness is located between 79.0 Mb and 82.5 Mb. In the investigated canine chromosomal region no obvious candidate gene for the IgE-responsiveness is located. The interval contains the IL34 gene encoding a member of the interleukin family, but this gene has so far not been implicated in the regulation of IgE levels [34]. Up till now, the genome region around the IL34 gene has not been associated with IgE levels in human GWAS [4].

At first glance, it may seem surprising that one locus should influence the allergen-specific IgE levels against A. siro, but none of the other allergens. This experimental finding is most likely due to the skewed distributions of IgE responders and non-responders with respect to the different antigens investigated. Our detailed analysis of dogs with “A. siro IgE non-responsive” and “A. siro IgE responsive” genotypes at the associated SNP revealed a consistent trend for lower IgE but not lower IgG levels across all antigens in the non-responsive genotype class (Figure 3). Thus, the detected locus on CFA 5 may in fact influence the IgE response in general rather than the IgE response to only A. siro. Further studies with increased cohort sizes are necessary to conclusively prove this hypothesis.

In conclusion, we mapped two loci for the IgE response to A. siro and T. putrescentiae, respectively, in Labrador Retrievers. There is no clear functional candidate gene within the associated regions. Thus, this study might eventually lead to the functional annotation of one or several orphan genes and facilitate a better understanding of the immune response to environmental antigens in dogs and humans.

Materials and Methods

Ethics statement

All animal experiments were performed according to the local regulations. The dogs in this study were examined with the consent of their owners. The study was approved by the “Cantonal Committee For Animal Experiments” (Canton of Bern; permits 22/07 and 23/10).

Animal selection

We collected 161 serum and EDTA blood samples from Labrador Retrievers, including 136 dogs with high A. siro-specific IgE and 25 dogs with low A. siro-specific IgE serum levels (see below). This work was part of a larger effort to build the LUPA...
AD cohort, which currently consists of 302 Labrador Retrievers. The dogs were clinically diagnosed according to established criteria for canine AD [35,36] by the clinical dermatology services of the Universities of Bern, London, Uppsala, Utrecht, or Zurich. Control dogs were also investigated by clinical dermatologists. Among dogs with elevated A. siro-specific IgE levels 61 were diagnosed as AD-affected and 75 as controls, whereas among dogs with low levels of A. siro-specific IgE 16 were AD-affected and 9 were controls. The samples were recruited from 2008–2010.

DNA samples and SNP genotyping

Genomic DNA samples were isolated from EDTA blood with the Nucleon Bace2 kit (GE Healthcare). The DNA was genotyped at the Centre National de Génopatoge, Evry, France using illumina canine_HD chips containing 174,376 SNP markers. Genotypes were stored in a BC/SNPmax Database version 3.4 (BC/Platforms).

Measurements of allergen-specific immunoglobulin serum levels

Allergen-specific serum IgE levels against Dermatophagoidea farinae, Dermatophagoidea pteronyssinus, Tyrophagus putrescentiae, Lepidoglyphus destructor, A. siro, Alternaria alternata, Cladosporium herbarum, Aspergillus fumigatus, Penicillium sp, cat epithelium, flea saliva, and Blatella germanica were measured by a commercially available test (Allercept™ IgE Test Panel, Heska AG, Fribourg, Switzerland) [37]. The Heska laboratory was not aware of the clinical diagnosis. The assay was considered as positive when the optical density measured at 405 nm was >150 EU. The threshold was set by the company by taking a large number of sera that tested very low in the assay which were then heated each at 56°C for 4 hours to inactivate IgE and tested again. Each heated serum in this group was defined as negative for allergen specific IgE. The mean EU value plus 3 standard deviations for the group of negative sera was calculated for each of the different allergens, and then an average mean plus 3 SD for all allergens was calculated (150 EU) and used as the cut off.

Total serum IgE levels were also determined by ELISA. Briefly: Plates (Thermo, VWR) were coated with anti-canine IgE monoclonal antibody D9 [38]. Blocking of non-specific binding sites followed, before addition of the test sera, or of purified canine IgE (Bethyl Laboratories, Inc.) used to generate a standard curve on each plate. The canine sera were serially twofold diluted starting at a dilution of 1:100. After incubation and washing, biotinylated monoclonal anti-canine IgE antibody D9 [38] was added for 1 h, followed by extravidine-alkaline phosphatase (Sigma). The plates were then developed with a of phosphatase

<table>
<thead>
<tr>
<th>SNP</th>
<th>Position</th>
<th>Alleles</th>
<th>Allele frequencies (136 cases/25 controls)</th>
<th>Praw*</th>
</tr>
</thead>
<tbody>
<tr>
<td>BICF2P13297212</td>
<td>79,522,993</td>
<td>G/A</td>
<td>0.04/0.33</td>
<td>2.14×10⁻⁴</td>
</tr>
<tr>
<td>BICF2P1022237</td>
<td>80,037,053</td>
<td>C/T</td>
<td>0.05/0.33</td>
<td>1.07×10⁻⁴</td>
</tr>
<tr>
<td>BICF2P1226027</td>
<td>81,633,676</td>
<td>G/A</td>
<td>0.03/0.24</td>
<td>5.36×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P1359501</td>
<td>81,697,025</td>
<td>G/A</td>
<td>0.03/0.24</td>
<td>5.36×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P501959</td>
<td>81,740,735</td>
<td>T/C</td>
<td>0.03/0.24</td>
<td>5.36×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P1096337</td>
<td>81,762,550</td>
<td>C/T</td>
<td>0.03/0.24</td>
<td>5.36×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P373634</td>
<td>80,027,563</td>
<td>C/T</td>
<td>0.03/0.26</td>
<td>6.20×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P641629</td>
<td>79,668,045</td>
<td>C/T</td>
<td>0.04/0.28</td>
<td>7.13×10⁻⁷</td>
</tr>
<tr>
<td>BICF2P1263867</td>
<td>78,984,517</td>
<td>C/T</td>
<td>0.04/0.30</td>
<td>1.12×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P526058</td>
<td>81,916,847</td>
<td>A/G</td>
<td>0.03/0.24</td>
<td>1.57×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P570236</td>
<td>81,927,096</td>
<td>C/T</td>
<td>0.03/0.24</td>
<td>1.57×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P89928</td>
<td>81,950,340</td>
<td>G/A</td>
<td>0.03/0.24</td>
<td>1.57×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P120791</td>
<td>79,047,969</td>
<td>T/G</td>
<td>0.04/0.26</td>
<td>1.75×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P03501</td>
<td>79,079,463</td>
<td>G/A</td>
<td>0.04/0.26</td>
<td>1.75×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P23308</td>
<td>79,008,866</td>
<td>T/G</td>
<td>0.04/0.26</td>
<td>1.91×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P159065</td>
<td>82,120,219</td>
<td>A/G</td>
<td>0.04/0.26</td>
<td>3.98×10⁻⁶</td>
</tr>
<tr>
<td>BICF2S3258772</td>
<td>82,134,285</td>
<td>C/T</td>
<td>0.04/0.26</td>
<td>3.98×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P18446</td>
<td>81,863,636</td>
<td>G/A</td>
<td>0.04/0.26</td>
<td>4.02×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P139695</td>
<td>81,869,371</td>
<td>A/G</td>
<td>0.04/0.26</td>
<td>4.02×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P1431</td>
<td>81,885,244</td>
<td>C/T</td>
<td>0.04/0.26</td>
<td>4.02×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P856483</td>
<td>81,892,362</td>
<td>C/T</td>
<td>0.04/0.26</td>
<td>4.02×10⁻⁶</td>
</tr>
<tr>
<td>TIGRP2P74638</td>
<td>82,033,585</td>
<td>G/A</td>
<td>0.04/0.24</td>
<td>4.15×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P23747</td>
<td>86,660,476</td>
<td>C/A</td>
<td>0.03/0.17</td>
<td>7.61×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P1319778</td>
<td>81,083,575</td>
<td>A/G</td>
<td>0.04/0.24</td>
<td>8.19×10⁻⁶</td>
</tr>
<tr>
<td>BICF2P142629</td>
<td>80,190,234</td>
<td>G/A</td>
<td>0.03/0.22</td>
<td>1.30×10⁻⁵</td>
</tr>
<tr>
<td>BICF2P64952</td>
<td>80,213,154</td>
<td>A/G</td>
<td>0.03/0.22</td>
<td>1.30×10⁻⁵</td>
</tr>
<tr>
<td>BICF2P132949</td>
<td>80,229,734</td>
<td>T/C</td>
<td>0.03/0.22</td>
<td>1.30×10⁻⁵</td>
</tr>
</tbody>
</table>

*p-values were calculated using χ² tests in an allelic association study.

doi:10.1371/journal.pone.0039176.t001
substrate (Sigma) in diethanolamine (Fluka) solution. Absorbance readings were measured at 405 nm. The values of the test sample were calculated from the standard curve using an ELISA software program (SOFTmax® 2.31 for Windows™, Molecular Devices Co., Sunnyvale, CA, USA).

Figure 2. Results of the genome-wide association study restricted to SNP markers located on CFA5. (A) GWAS in the cohort of 161 Labradors showed a significant association of the elevated *A. siro* specific IgE levels in 136 *A. siro* IgE-positive dogs and 25 *A. siro* IgE-negative dogs. (B) Associated SNP markers (black) and minor allele frequency (green) at the locus of the IgE-responsiveness to *A. siro* zoomed into the interval between 75 Mb and 85 Mb. (C) The gene content of the 3.5-Mb chromosomal interval estimated according to the dog build 2 and displayed using UCSC Genome Browser (http://genome.ucsc.edu). doi:10.1371/journal.pone.0039176.g002
Table 2. Genome-wide association results with respect to all studied traits.

<table>
<thead>
<tr>
<th>Allergen</th>
<th>Responders (cases)</th>
<th>Non-responders (controls)</th>
<th>Chromosome&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Best associated SNP</th>
<th>Position</th>
<th>p&lt;sub&gt;raw&lt;/sub&gt;</th>
<th>No. of associated SNPs&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acarus siro IgE</td>
<td>136</td>
<td>25</td>
<td>5</td>
<td>BICF2S2297212</td>
<td>79,522,993</td>
<td>2.14×10⁻⁶</td>
<td>8</td>
</tr>
<tr>
<td>Tyrophagus putrescentiae IgE</td>
<td>145</td>
<td>16</td>
<td>5</td>
<td>BICF2G630182886&lt;sup&gt;c&lt;/sup&gt;</td>
<td>33,656,088</td>
<td>6.10×10⁻⁶</td>
<td>6</td>
</tr>
<tr>
<td>Blattella germanica IgE</td>
<td>10</td>
<td>151</td>
<td>14</td>
<td>BICF2P1257596</td>
<td>62,500,248</td>
<td>9.92×10⁻⁷</td>
<td>1</td>
</tr>
<tr>
<td>Cat epithelium IgE</td>
<td>13</td>
<td>148</td>
<td>14</td>
<td>BICF2P1257596</td>
<td>62,500,248</td>
<td>9.92×10⁻⁷</td>
<td>1</td>
</tr>
<tr>
<td>Aspergillus fumigatus IgE</td>
<td>13</td>
<td>148</td>
<td>14</td>
<td>BICF2P1257596</td>
<td>62,500,248</td>
<td>9.92×10⁻⁷</td>
<td>1</td>
</tr>
<tr>
<td>Penicillium sp. IgE</td>
<td>11</td>
<td>150</td>
<td>7</td>
<td>BICF2P140154</td>
<td>10,490,910</td>
<td>1.30×10⁻⁶</td>
<td>0</td>
</tr>
<tr>
<td>Flea saliva IgE</td>
<td>17</td>
<td>144</td>
<td>3</td>
<td>BICF2S2259970</td>
<td>25,656,748</td>
<td>3.31×10⁻⁶</td>
<td>0</td>
</tr>
<tr>
<td>Dermatophagoides pteronyssinus IgE</td>
<td>75</td>
<td>86</td>
<td>14</td>
<td>BICF2P471228</td>
<td>62,894,579</td>
<td>8.78×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Total IgE</td>
<td>93</td>
<td>68</td>
<td>7</td>
<td>BICF2G630551420</td>
<td>14,468,374</td>
<td>1.75×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Dermatophagoides farina IgE</td>
<td>133</td>
<td>15</td>
<td>14</td>
<td>BICF2P45581</td>
<td>37,505,424</td>
<td>3.19×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Alternaria alternate IgE</td>
<td>53</td>
<td>108</td>
<td>6</td>
<td>BICF2S22949377</td>
<td>30,641,636</td>
<td>3.91×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Dermatophagoides farinae IgG1</td>
<td>67</td>
<td>81</td>
<td>12</td>
<td>BICF2P376143</td>
<td>51,541,485</td>
<td>4.02×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Lepidoglyphus destructor IgE</td>
<td>24</td>
<td>137</td>
<td>12</td>
<td>BICF2P376143</td>
<td>51,541,485</td>
<td>5.81×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Cladosporium herbarum IgE</td>
<td>12</td>
<td>149</td>
<td>36</td>
<td>BICF2G630756211</td>
<td>31,175,618</td>
<td>7.09×10⁻⁵</td>
<td>0</td>
</tr>
<tr>
<td>Dermatophagoides farinae IgG4</td>
<td>72</td>
<td>76</td>
<td>12</td>
<td>BICF2P376143</td>
<td>51,541,485</td>
<td>7.77×10⁻⁵</td>
<td>0</td>
</tr>
</tbody>
</table>

Associations exceeding the Bonferroni-corrected significance threshold of p<sub>raw</sub> = 4.4×10⁻⁷ are shown in bold.

*Chromosome with the best associated marker.

<sup>b</sup>Number of SNPs at the locus with p<sub>raw</sub> < 10⁻⁷. Purebred dogs typically show long-range linkage disequilibrium within breeds. Therefore, strong association signals within dog breeds are often associated by multiple SNPs within a 1–2 Mb interval.

<sup>c</sup>This SNP had a p-value of 7.66×10⁻⁵ in the GWAS with respect to A. siro specific IgE levels. T. putrescentiae and A. siro both belong to the group of storage mites. doi:10.1371/journal.pone.0039176.t002
Relative concentration of the IgG subclasses IgG1 and IgG4, specific for *Dermatophagoides farinae* were determined in the sera of AD and control dogs. 96 well plates (Thermo, VWR) were coated with *Dermatophagoides farinae* extract (Allergomed AG, 4106 Therwil, Switzerland). After blocking, dog sera were serially twofold diluted and added to the plate. A serum pool from dogs immunized with *Dermatophagoides farinae* was used to generate a standard curve on each plate. After incubation and washing, monoclonal antibodies specific for canine IgG1 (clone B6) or IgG4 (clone A5) were added to the plates [40]. An alkaline phosphatase-conjugated affinity purified goat anti-mouse IgG (Jackson ImmunoResearch Inc.) followed. Plates were then developed with phosphatase substrate. Absorbance readings and calculating of IgG1 or IgG4 levels in relative ELISA units were performed as described above.

The *Dermatophagoides farinae* specific IgG1 and IgG4 as well as the total IgE serum levels were transformed into categorical traits by using the median as cut off.

**Genome-wide association studies**

We used GenABEL [41] to perform genome-wide association analyses (GWAS). We removed markers with call rates <95% and individuals with call rates <90% from the analysis. For analyses with respect to *Dermatophagoides farinae* specific immunoglobulin levels (IgG1, IgG4, IgE), we removed 13 dogs that had received allergen-specific immunotherapy with *Dermatophagoides farinae* extracts. We also removed markers with minor allele frequency (MAF) <5% and markers strongly deviating from Hardy-Weinberg equilibrium (p<10^-5). We performed an allelic association study using the h2a2 function, which uses the kinship matrix estimated from the marker data to correct for population stratification. Significance levels were determined by the Bonferroni correction (P_{Bonf} = 0.05/number of markers). Additionally, empirical significance thresholds were also determined by performing 100,000 permutations of the dataset with arbitrarily assigned phenotypes.

**Gene analysis**

We used the dog build 2 and the human build 37 assemblies for all analyses. We used BLASTN searches to define the orthologous human chromosomal regions corresponding to the associated interval on CFA 5. For the candidate gene inspection we used the human annotation provided by NCBI (build 37.3).

**Supporting Information**

Figure S1 Multidimensional scaling (MDS) plot showing the genomic kinships between the analyzed Labrador Retrievers. This plot visualizes the overall genetic distances between the dogs based on 2,000 markers randomly selected out of the total of 113,021 SNP markers. Cases and controls do not form separate clusters, which is an essential prerequisite for a successful GWAS.

(TIF)

**Acknowledgments**

The authors are grateful to referring veterinarians and to all dog owners and breeders who donated blood and serum samples and shared pedigree data. We thank Doug J. DeBoer and Bruce Hammerberg for supplying antibodies and we appreciate the technical assistance of Brigitta Colomb, Christoph Prii, and Susanne Roth. We thank Heska and especially Dr. Michal Dörer and his team for the very efficient determination of allergen-specific IgE levels.
Author Contributions

Conceived and designed the experiments: PR EM TL. Performed the experiments: MO-L BL VM SM. Analyzed the data: MO-L BL MK KT.

References
