Effective Detection of Human Leukocyte Antigen Risk Alleles in Celiac Disease Using Tag Single Nucleotide Polymorphisms

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

Citation

Published Version
doi:10.1371/journal.pone.0002270

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:5343417

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA
Effective Detection of Human Leukocyte Antigen Risk Alleles in Celiac Disease Using Tag Single Nucleotide Polymorphisms

Alienke J. Monsuur1*, Paul I. W. de Bakker2,9, Alexandra Zhernakova1, Dalila Pinto3, Willem Verduijn3, Jihane Romanos4, Renata Auricchio5, Ana Lopez6, David A. van Heel7, J. Bart A. Crusius8, Cisca Wijmenga1,4*

1Department of Medical Genetics, University Medical Centre Utrecht, Utrecht, The Netherlands, 2Broad Institute of Harvard and Massachusetts Institute of Technology (MIT), Cambridge, United States of America, 3Section for Immunogenetics and Transplantation Immunology of the Department of Immunohematology and Blood Transfusion (IHb), Leiden University Medical Center (LUMC), Leiden, The Netherlands, 4Genetics Department, University Medical Centre Groningen and University of Groningen, Groningen, The Netherlands, 5Department of Pediatrics and European Laboratory for the Investigation of Food-Induced Diseases, University Federico II Naples, Naples, Italy, 6Pediatric Gastroenterology Unit, Fundación Investigación Hospital La Fe, Valencia, Spain, 7Institute of Cell and Molecular Science, Barts and the London School of Medicine and Dentistry, London, United Kingdom, 8Department of Pathology, Vrije Universiteit (VU) University Medical Centre, Amsterdam, The Netherlands, 9Division of Genetics, Brigham and Women’s Hospital, Harvard-Partners Center for Genetics and Genomics, Boston, United States of America

Abstract

Background: The HLA genes, located in the MHC region on chromosome 6p21.3, play an important role in many autoimmune disorders, such as celiac disease (CD), type 1 diabetes (T1D), rheumatoid arthritis, multiple sclerosis, psoriasis and others [1–3]. The MHC region is highly polymorphic and some genes in this region are involved in multiple disorders. For example, the HLA-DQA1 and -DQB1 genes have alleles that confer risk to both CD and T1D. In most autoimmune diseases not all patients carry the same risk alleles, and multiple risk alleles are likely to be involved [2]. CD, the most common intolerance to a dietary component in Western society, is sustained by an abnormal T cell response to gluten as an environmental factor and is strongly associated with

Conclusion: Using this method, only six SNPs were needed to predict the risk types carried by >95% of CD patients. We determined that for this tagging approach the sensitivity was >0.991, specificity >0.996 and the predictive value >0.948. Our results show that this tag SNP method is very accurate and provides an excellent basis for population screening for CD. This method is broadly applicable in European populations.


Editor: Peter Heutink, Vrije Universiteit Medical Centre, Netherlands

Received January 30, 2008; Accepted April 3, 2008; Published May 28, 2008

Competing Interests: The HLA-DQ haplotyping was invented at the University Medical Centre Utrecht and will be developed and marketed by Genome Diagnostics BV. The UMC Utrecht may receive royalties from the worldwide sale of the technology. UMC Utrecht may distribute part of the royalty revenues to the inventors (CW and AM). None of the authors report a financial or other link with Genome Diagnostics BV. Genome Diagnostics had no role in study design, data collection and analysis, decisions to publish, or preparation of the manuscript.

* E-mail: c.wijmenga@umcutrecht.nl

Current address: Dutch Vaccine Institute, Bilthoven, The Netherlands

Introduction

The HLA genes, located in the major histocompatibility (MHC) region on chromosome 6p21.3, play a role in multiple autoimmune disorders, like celiac disease (CD), type 1 diabetes (T1D), rheumatoid arthritis, multiple sclerosis, psoriasis and others [1–3]. The MHC region is highly polymorphic and some genes in this region are involved in multiple disorders. For example, the HLA-DQA1 and -DQB1 genes have alleles that confer risk to both CD and T1D. In most autoimmune diseases not all patients carry the same risk alleles, and multiple risk alleles are likely to be involved [2].

CD, the most common intolerance to a dietary component in Western society, is sustained by an abnormal T cell response to gluten as an environmental factor and is strongly associated with
HLA class II genes. Almost 95% of CD patients carry at least one of the two risk molecules DQA1*05/DQB1*02 (i.e. haplotype DQ2.5) and DQA1*03/DQB1*0302 (i.e. haplotype DQ8) [2,4–7]. The molecules encoded by the CD-associated HLA-DQA1 and -DQB1 genes form DQα and DQβ heterodimers, which can lead to several functional molecules of which one to four copies can be made. A few variants of these genes predispose to CD (either alone or in combination) when gluten peptides, present in wheat, barley and rye, are presented to CD4+ cells in the lamina propria [8,9]. The most important risk factor for CD is the DQ2.5 haplotype (see Figure 1 and Table 1) [5,10,11], with the highest risk in individuals homozygous for this haplotype [8,12], or those who have a single copy of DQ2.5 and one copy of DQA1*0201/DQB1*0202 (i.e. haplotype DQ2.2) molecules, haplotype DQ8, or DQA1*0505/DQB1*0301 (i.e. haplotype DQ7). The frequency of these alleles in the general population is substantial (>25%), suggesting that these variants are necessary for disease development but not sufficient.

Family-based or population-based screening for the CD risk variants has important diagnostic value in supporting the diagnosis of CD when these alleles are present, and the possibility of CD is minimized when they are not present (they have a high negative predictive value). In a recent study by Bourgey et al. [13] it was shown that the risk estimates of a sibling of a CD patient ranges from 0.1% to 29% when HLA-DQ information is included, compared to the overall risk for sibs of approx. 10%. CD affects almost 1% of the population, although it is estimated that most cases remain undiagnosed [14]. Since untreated CD can cause long-term health problems, targeted screening in e.g. families for CD could identify such undiagnosed individuals and prevent lifelong symptoms and complications.

Testing for HLA risk molecules is routinely performed using specialized kits, but they often require 24–60 reactions, multiple steps, like amplification and hybridization to a membrane, special software or expertise in analyzing the results and most of these methods are expensive (e.g. DNA PCR-single-strand conformation polymorphism [PCR-SSCP] [15], PCR and sequence specific oligonucleotide probing [PCR-SSOP] [16], PCR-sequence specific primer kits [PCR-SSP] [17], PCR-reverse line blot (PCR-RLB) [18]).

Direct typing of the genetic variants that encode the HLA alleles is usually very difficult since most of these variants are surrounded by too many other variants that interfere with primer annealing.

The International HapMap Project and an independent MHC-focused effort [19,20] have empirically determined the fine-scale patterns of linkage disequilibrium (LD) among local sequence polymorphisms in four population samples. With these resources it is now possible to pick tag SNPs that are in LD with specific HLA variants of interest (i.e. have high \(r^2\) values). Recently, an LD-based tagging approach was shown to predict HLA-DQ2.2 and –DQ5 alleles in independent patient samples with a high degree of accuracy [20].

In this study we selected tag SNPs to predict DQ2.2, DQ2.5, DQ7 and DQ8, in three cohorts: CD patients, non-CD trio control families, and blood bank controls (HLA typing was available for all individuals). We then examined the sensitivity, specificity, predictive value and the correlation between the SNP-based test and the true HLA variant (\(r^2\)). This study represents a first step towards providing a cost-effective population screening method for CD.

### Table 1. Genetic risk associated with the different HLA-DQ molecules

<table>
<thead>
<tr>
<th>DQ molecule 1</th>
<th>DQ molecule 2</th>
<th>Number of functional copies</th>
<th>Genetic risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQ2.5</td>
<td>Non-CD risk types</td>
<td>≥1</td>
<td>5.5</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>Non-CD risk types</td>
<td>4</td>
<td>13.1</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>no DQ2.2, DQ2.5, DQ7</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>no DQ2.5</td>
<td>1–2</td>
<td>2.5</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>DQ2.2</td>
<td>2</td>
<td>10.1</td>
</tr>
<tr>
<td>DQ2.2 or DQ2.5</td>
<td>Non-CD risk types</td>
<td>1–4</td>
<td>24.4</td>
</tr>
<tr>
<td>DQ2.2</td>
<td>DQ7</td>
<td>1</td>
<td>1.8*</td>
</tr>
<tr>
<td>DQ2.2</td>
<td>no DQ2.5, DQ7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>DQ7</td>
<td>no DQ2.2, DQ2.5</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>DQ7</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>DQ8</td>
<td>Non-CD risk types</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>DQ8</td>
<td>DQ8</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^*\)This risk increases to 4.1 in the DQ2.5 negative group.

![Figure 1. HLA-DQA1* and -DQB1* together form heterodimers of which DQ2.5 and DQ8, either in homozygous or heterozygous state, confer risk to CD due to their ability to present gluten to T cells. DQ2.2 and DQ7 can only confer risk to CD when both are present together or with DQ2.5 (trans effect, see dashed lines). See Table 1 for the possible combinations, the number of risk molecules and the associated risk. doi:10.1371/journal.pone.0002270.g001](image)
both the SNP retyping and official retyping, so we cannot fully rule out the possibility of DNA switching leading to false-positive or false-negative results.

For each DQ type we used all persons with non-missing data for the relevant SNPs. A person with missing data for DQ2.5, for example, was excluded from the DQ2.5 analysis, but could be used for the other analyses if genotypes relevant for the other DQ types were present.

At first the sensitivity and specificity for DQ2.2 was high and accurate but the predictive value was low. The SNPs for DQ2.2 (rs2395182, rs7775228) not only tagged DQ2.2 but also included the relatively infrequent DQ4 allele. We therefore decided to tag DQ4 as well (rs4713586) making it possible to call a person DQ2.2 when the alleles were positive for DQ2.2 and negative for DQ4. This led to three tag SNPs being needed for the prediction of DQ2.2, with an overall sensitivity of 0.992, a specificity of 0.998 and a PPV of 0.977. Only four of the 1448 tested chromosomes gave false results (0.28%).

The tag SNP selected for DQ2.5 (rs2187668) showed an overall sensitivity of 1.000, a specificity of 0.999 and a PPV of 0.998. Only one of the 1450 tested chromosomes gave false results (0.07%). This person did indeed carry half of the DQ2.5 haplotype (DQA1*0501) (see Table S3b, person nos. 10).

The tag SNP for DQ8 (rs7454108) showed an overall sensitivity of 0.991, a specificity of 0.996 and a PPV of 0.948. Seven of the 1484 tested chromosomes gave false results (0.5%).

Accepting the prediction of these half haplotypes as good predictions of the risk alleles increases the sensitivity, specificity and PPV slightly.

To validate our results in other populations, we additionally tested the same SNP panel in 76 HLA-typed individuals from the “prevenCD” study populations (a family based celiac disease study) from Valencia (Spain) (n = 32) and Naples (Italy) (n = 44). In addition, we previously reported on the performance of the DQ2.5 predictive SNP rs2187668 SNP in 262 HLA-typed celiac cases from the UK as part of a genome-wide association study [23]. The overall sensitivity and specificity in the UK celiac population was similar to what was observed in the Dutch celiac population. In the Spanish and Italian celiac cohort a few samples showed discordance for the DQ2.5 and DQ7 haplotype, giving rise to slightly lower $r^2$ values for this prediction. Prediction values for DQ2.2 and DQ8 in both Spanish and Italian celiac samples were similar to the Dutch results (Table S4).

Discussion

In this study we used a tag SNP approach to predict whether an individual carried the risk DQ types (formed by variants in the HLA-DQA1 and -DQB1 genes) that are positively associated with CD. Using this method, only six SNPs were needed to predict the DQ2.2, DQ2.5, DQ7 and DQ8 risk types carried by >95% of CD patients. We determined that for this tagging approach the sensitivity was >0.991, specificity >0.996 and the predictive value >0.948.

Most of the patients without DQ2.5 and DQ8, carried half of the DQ2.5 or DQ2.2 molecule (either HLA-DQA1*05 or -DQB1*0202) suggesting that carrying part of the risk molecules has functional implications for the risk of CD [4,22]. Of our patient group 98.4% carry one of the risk groups (DQ2.2, DQ2.5, DQ7, DQ8 or the DQ types that have half of the risk haplotypes) and 98.3% of all patients were correctly predicted using our method. Overall, the sensitivity was 0.997, the specificity was >0.992 and predictive value was >0.987 when taking into account that some of the false predictions included an allele that is part of a risk haplotype (e.g. the HLA-DQA1*05 allele which is part of the DQ2.5 haplotype, see person nos. 10–12 in Table S3b).

This method also allowed us to determine whether an individual was homozygous or heterozygous for the risk molecule. Vader et al. demonstrated a 4-fold higher T cell response when gluten was presented by antigen-presenting cells from DQ2 homozygous patients compared to DQ2 heterozygous patients, thereby providing an explanation for the dose-effect of risk molecules for developing CD [9]. Al-Toma et al. showed that homozygosity for DQ2.5 was seen more than twice as often in individuals that developed refractory celiac disease and enteropathy-associated T-cell lymphoma, associated with a high morbidity, than in uncomplicated CD [12].

Reinton et al. developed a real-time PCR method for detecting CD-associated HLA risk alleles [23]. This method requires 11 reactions and even more if homozygous persons for the HLA-risk alleles need to be distinguished from heterozygous persons. It is not clear whether this real-time PCR method can be easily applied to high-throughput typing or not, whereas our method can. We can perform PCR reactions in multiple PCR machines at the same time and use the ABI PRISM 7900 HT system only for end-point measurements. Moreover, Reinton et al. only used a relatively small set of samples to test their method, making it difficult to determine its robustness.

Table 2. Prediction results for combined cohorts

<table>
<thead>
<tr>
<th></th>
<th>SNP prediction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DQ2.2</td>
<td>+</td>
<td>−</td>
<td>total sensitivity 0.992</td>
</tr>
<tr>
<td></td>
<td>126</td>
<td>3</td>
<td>129 specificity 0.998</td>
</tr>
<tr>
<td></td>
<td>− 1</td>
<td>1318</td>
<td>1319 positive predictive value 0.977</td>
</tr>
<tr>
<td>total</td>
<td>127</td>
<td>1321</td>
<td>1448 r-squared 0.966</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>+</td>
<td>−</td>
<td>total sensitivity 1.000</td>
</tr>
<tr>
<td></td>
<td>569</td>
<td>1</td>
<td>570 specificity 0.999</td>
</tr>
<tr>
<td></td>
<td>− 0</td>
<td>888</td>
<td>888 positive predictive value 0.998</td>
</tr>
<tr>
<td>total</td>
<td>569</td>
<td>889</td>
<td>1458 r-squared 0.997</td>
</tr>
<tr>
<td>DQ7</td>
<td>+</td>
<td>−</td>
<td>total sensitivity 1.000</td>
</tr>
<tr>
<td></td>
<td>94</td>
<td>4</td>
<td>98 specificity 0.997</td>
</tr>
<tr>
<td></td>
<td>− 0</td>
<td>1372</td>
<td>1372 positive predictive value 0.959</td>
</tr>
<tr>
<td>total</td>
<td>94</td>
<td>1376</td>
<td>1470 r-squared 0.956</td>
</tr>
<tr>
<td>DQ8</td>
<td>+</td>
<td>−</td>
<td>total sensitivity 0.991</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>6</td>
<td>116 specificity 0.996</td>
</tr>
<tr>
<td></td>
<td>− 1</td>
<td>1367</td>
<td>1368 positive predictive value 0.948</td>
</tr>
<tr>
<td>total</td>
<td>111</td>
<td>1373</td>
<td>1484 r-squared 0.935</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0002270.t002
De Bakker et al. showed two examples that used the tagging method for CD and systemic lupus erythematosus [20]. They chose two SNPs to capture DQ2.2 and DQ2.5 in the same CD cohort (N = 390) that we have used in this paper. The rs4988889(T), rs2858331(C) haplotype was used to determine the presence of DQ2.2 and the rs4988889(T), rs2858331(T) haplotype was used to determine DQ2.5. Although the SNPs look promising in determining DQ2.5 homozygosity or DQ2.2/DQ2.5 heterozygosity, it was often difficult to distinguish DQ2.2/X heterozygosity from the DQ2.5/X heterozygous individuals (X is any other allele excluding DQ2.2 or DQ2.5), due to the uncertainty of the alleles at the two SNPs. An individual who is homozygous for rs4988889 (G/T) has one copy of DQ2.2 or DQ2.5. If he/she is also heterozygous for rs2858331 (C/T), then it is uncertain which of these alleles (either C or T) is on the same chromosome as the T allele of rs498889 and therefore forms either DQ2.2 or DQ2.5. In contrast to these examples are the SNPs we used in the current study, which are capable of determining whether an individual is homozygous for DQ2.2 or DQ2.5, heterozygous for DQ2.2 or DQ2.5, or does not possess the DQ2.2 or DQ2.5 haplotype at all.

We expect the chosen tag SNPs to be transferable within European populations given the strong conservation of the HLA-DR3-DQ2 haplotype. De Bakker et al. has given two examples that show that tag SNPs chosen from the CEU panel (CEPH (Utah residents with ancestry from northern and western Europe)) are applicable in other populations and our data also gives similar r^2 values to the CEU panel [20]. The r^2 might be somewhat higher or lower in the population that it is applied to, with a resulting gain or loss of power, but the differences observed are minimal. We have also seen that the tag SNP for DQ2.5 tested in an UK population gives comparable results (UK population: r^2 0.96, Dutch population: r^2 (0.99) [21]. Analysing the tag SNPs in two southern European populations – from Italy and Spain – gives comparable results (UK population: r^2 0.96, Dutch population: r^2 0.99) [21].

Analysing the tag SNPs in two southern European populations – from Italy and Spain – gives comparable results (UK population: r^2 0.96, Dutch population: r^2 0.99) [21]. Analysing the tag SNPs in two southern European populations – from Italy and Spain – gives comparable results (UK population: r^2 0.96, Dutch population: r^2 0.99) [21].

We have described a robust method to predict the risk DQ types involved in CD with high accuracy. This method can also be applied to T1D, in which DQ2.5 and DQ8 are also known risk factors, or more generally for other immune-related diseases with known HLA risk alleles.

Materials and Methods

DNA samples

DNA was available from three different cohorts; these were used to study different aspects of the tag SNP method. The CD cohort had a high number of individuals with HLA-DQ2 risk variants, which was useful for testing the positive predictive value. The trio control cohort enabled us to check for Mendelian errors (which were not observed), while the blood bank controls gave a better view of the robustness of the method in the general population. The first cohort consisted of 330 unrelated CD patients of Dutch Caucasian origin [24]. Only CD patients diagnosed according to revised ESPGHAN criteria and with a Marsh III lesion confirmed by duodenal biopsy sampling were selected for this study, as described by Van Belzen et al. [25] and Walker-Smith et al. [26]. A cohort of population-based control trios was derived from families without a history of CD [27]. The 86 control trios were selected for the presence of at least one parent carrying haplotype DQ2.5 and were all of Dutch Caucasian origin. HLA typing data was available for 207 of the 264 persons in the 86 trios (see below), of these 2 persons dropped out for all SNPs typed and were excluded from this paper. The blood bank cohort was part of the ITI two panel (the ITI panel is a DNA panel from the Immunogenetics and Transplantation Immunology Section of the LUMC) and consisted of 219 unrelated, randomly selected, Dutch blood donors. We studied a total of 754 persons. The study was approved by the Medical Ethics Committee of the University Medical Centre Utrecht, and informed consent was obtained from the participants.

The replication cohort includes 32 HLA-typed Spanish celiac samples from Valencia and 44 HLA-typed Italian celiac samples from Naples. These two study samples form part of the “preventCD” study, a European multicenter study. The 262 CD-haplotype UK celiac cases were recently included in a genome-wide association study [21].

HLA typing

The CD cohort and the trio control cohort were typed for HLA-DQA1 and -DQB1 genes using a classical PCR-SSCP/heteroduplex method in an official HLA typing laboratory as described elsewhere [12,15]. Full HLA-DQA1 and -DQB1 typing was available for the entire CD cohort. For the trio control cohort, full HLA-DQA1 and -DQB1 typing was available for the child and both parents in 34 trios and for the child and one of the parents in 51 trios, and for one trio only one person could be SNP typed leading to a total of 205 persons available for analyses. For the blood bank control cohort, full (four digit) HLA-DRB1, -DQA1 and -DQB1 typing was performed by PCR-SSCP using locally produced and slightly modified primer mixes [28]. The typing of this cohort was performed in the European Foundation of Immunogenetics (EFI)-accredited HLA laboratory of the Department of HBD, LUMC, Leiden. The typing of UK samples were performed at the Transplant Immunology laboratory, Oxford.
Table 3. DQ molecules and tested tag SNPs

<table>
<thead>
<tr>
<th>DQ type</th>
<th>DQA1</th>
<th>DQB1</th>
<th>DR</th>
<th>tag SNP</th>
<th>Positive predicting allele(s) (freqCEU)</th>
<th>tag SNP</th>
<th>Negative predicting allele</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQ2.2</td>
<td>0201</td>
<td>0202</td>
<td>7</td>
<td>rs2395182, rs7775228</td>
<td>T (0.71), G (0.10)</td>
<td>rs4713586</td>
<td>G (0.025)</td>
</tr>
<tr>
<td>DQ2.5</td>
<td>0501</td>
<td>0201</td>
<td>3</td>
<td>rs2187668</td>
<td>T (0.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQ7</td>
<td>0505</td>
<td>0301</td>
<td>5</td>
<td>rs4639334</td>
<td>A (0.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQ8</td>
<td>0301</td>
<td>0302</td>
<td>4</td>
<td>rs7454108</td>
<td>G (0.18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) DQ molecules, the corresponding HLA-DQA1* and -DQB1* alleles, with the DR type and the tag SNPs. A person that has the T,G,G haplotype for rs2395182, rs7775228, rs4713586, is a DQ2.2.

A person that has the T,G,G haplotype for rs2395182, rs7775228, rs4713586, is not a DQ2.2 but a DQ4.

FREQ(CEU) – frequency of annotated alleles in CEU HapMap population.

Analyses

The HLA-DQA1 and -DQB1 genotypes as determined at the HLA-typing centres were used to establish the corresponding DQ types (see Figure 1). Due to the high linkage disequilibrium in the MHC region, only a limited set of DQA1*-DQB1* haplotypes (DQ types) are observed in the general population (see http://depts.washington.edu/rhwlab/resMat/dq/linkage.html for an example of common combinations of DQA1* and DQB1* alleles in the Caucasian population), resulting in only a few instances that did not correspond to canonical DQ types. For the prediction method we inferred DQ types from the tag SNPs. DQ types were determined according to the predicting alleles (see Table 3, e.g. a person was called homozygous DQ8 if rs7454108 was homozygous G, or heterozygous DQ8 if rs7454108 was heterozygous G/A). Only individuals with non-missing data were used for comparing the official typing and the prediction method. DQ types based on the official typing and those from the tag SNP typing method were compared to examine the sensitivity, specificity, positive predictive value (PPV) and r^2.

Supporting Information

Table S1

Found at: doi:10.1371/journal.pone.0002270.s001 (0.05 MB DOC)

Table S2

Found at: doi:10.1371/journal.pone.0002270.s002 (0.13 MB DOC)

Table S3

Found at: doi:10.1371/journal.pone.0002270.s003 (0.05 MB DOC)

Table S4

Found at: doi:10.1371/journal.pone.0002270.s004 (0.08 MB DOC)

Acknowledgments

We thank all healthy individuals, the patients, their physicians, and the Dutch Coeliac Disease Foundation for participating in this study. We thank Harry van Someren as database manager and Jackie Senior for critically reading the manuscript.

Author Contributions

Conceived and designed the experiments: CW. Performed the experiments: AM AZ DP JR. Analyzed the data: AM AZ. Contributed reagents/materials/analysis tools: Pd WV Dv BC RA AL. Wrote the paper: Pd CW AM AZ.
References