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Characterization of Genetic Loci That Affect Susceptibility to Inflammatory Bowel Diseases in African Americans

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Abstract

Background & Aims—Inflammatory bowel disease (IBD) has familial aggregation in African Americans (AAs), but little is known about the molecular genetic susceptibility. Mapping studies using the ImmunoChip genotyping array expand the number of susceptibility loci for IBD in Caucasians to 163, but the contribution of the 163 loci and European admixture to IBD risk in AAs is unclear. We performed a genetic mapping study using the ImmunoChip to determine whether IBD susceptibility loci in Caucasians also affect risk in AAs and identify new associated loci.

Methods—We recruited AAs with IBD and without IBD (controls) from 34 IBD centers in the US; additional controls were collected from 4 other immunoChip studies. Association and admixture loci were mapped for 1088 patients with Crohn's disease (CD), 361 with ulcerative colitis (UC), 62 with IBD type-unknown (IBDU), and 1797 controls; 130,241 autosomal single-nucleotide polymorphisms (SNPs) were analyzed.

Results—The strongest associations were observed between UC and HLA rs9271366 ($P=7.5e-6$), CD and 5p13.1 rs4286721 ($P=3.0e-6$), and IBD and *KAT2A* rs730086 ($P=2.3e-6$). Additional suggestive associations ($P<4.2e-5$) were observed between CD and IBD and African-specific SNPs in *STAT5A* and *STAT3*; between IBD and SNPs in *IL23R*, *IL12B*, and C2 open reading frame 43; and between UC and SNPs near *HDAC11* and near *LINC00994*. The latter 3 loci have not been previously associated with IBD, but require replication. Established Caucasian associations were replicated in AAs ($P<3.1e-4$) at *NOD2*, *IL23R*, *5p15.3*, and *IKZF3*. Significant admixture ($P<3.9e-4$) was observed for 17q12-17q21.31 (*IKZF3* through *STAT3*), 10q11.23-10q21.2, 15q22.2-15q23, and 16p12.2-16p12.1. Network analyses showed significant

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enrichment (false discovery rate $<1e-5$) in genes that encode members of the JAK–STAT, cytokine, and chemokine signaling pathways, as well those involved in pathogenesis of measles.

Conclusions—In a genetic analysis of 3308 AA IBD cases and controls, we found that many variants associated with IBD in Caucasians also showed association evidence with these diseases in AAs; we found evidence for loci and variants not previously associated with IBD. The complex genetic factors that determine risk for or protection from IBD in different populations require further study.

Keywords

race; ethnicity; genetic variant; intestinal inflammation

Introduction

Inflammatory bowel disease (IBD) is a complex genetic disorder of immune dysregulation causing chronic idiopathic inflammation of the gastrointestinal tract, estimated to affect about 1.4 million Americans. It comprises two major, genetically related phenotypes: Crohn's disease (CD) and ulcerative colitis (UC).

IBD shares many clinical and immunological characteristics with other complex genetic immune-mediated diseases (IMDs), especially with seronegative auto-inflammatory diseases¹, such as ankylosing spondylitis, psoriasis and primary immune-deficiencies², indicating overlapping etiological factors. To facilitate genetic studies on IMDs a custom Illumina array of ~200,000 SNPs, the Immunochip, was designed based on genome wide association (GWA) analyses on Caucasian populations of 12 IMDs including IBD³. The main purposes were to fine map established associations and to replicate suggestive, but not yet proven, associations³. The Immunochip also contains ancestry informative markers (AIMs) allowing for genome-wide admixture estimates and adjustment for population stratification.

IBD GWA studies, including those performed using the Immunochip, have expanded the number of IBD susceptibility loci to 163 (including 30 CD- and 23 UC-specific loci)², and have enhanced our understanding of IBD immunopathogenesis by identifying key cellular pathways, both known – such as barrier function, the role of T cell subsets and cytokine–cytokine receptor signaling – and unknown – such as autophagy, regulation of interleukin 23 (IL23) signaling, and host defense⁴. However, compared to hundreds of IBD genetic studies in Caucasian populations including massive GWA mega-analyses and replication studies like the Caucasian Immunochip Study (CIS)², only a handful of IBD-associated gene variations have been evaluated in African Americans (AAs), in relatively small sample sizes of a few hundred cases and controls, and only for CD, not UC⁵⁻⁷.

AAs are a recently admixed population derived from an average of approximately 80% West African and 20% European ancestries⁸. IBD prevalence is lower in AAs than Caucasian Americans (CAs) possibly as a result of both genetic and environmental differences⁹⁻¹¹. IBD sibling risk in AA IBD patients is relatively high (2.5%), suggesting underlying genetic

risk factors are in-part responsible for IBD in AAs, albeit lower than that observed for Caucasians (4.6%)¹².

An admixed population is one where two or more previously separated populations have interbred. Loci that have different allele frequencies in the founder populations become correlated because of gene flow, a phenomenon known as admixture linkage disequilibrium (ALD). AAs are a typical example of an admixed population, where there has been recent introduction of European genetic lineages into a West-African-derived population. A powerful technique called mapping by ALD (MALD) can be used on admixed populations such as AAs and the underlying assumption is that the difference in disease frequency is due in part to differences in allele frequencies of causal variants between populations.

We therefore undertook an evaluation of the Immunochip in ~4000 AA IBD cases and controls, primarily to determine the importance of the 163 established CIS IBD loci in the understudied AA population and to identify novel IBD loci, including loci identified by MALD.

Patients and Methods

Study Population and Phenotyping

The study population included unrelated self-identified non-Hispanic AA volunteers recruited from three coordinating centers: (1) Johns Hopkins: Multicenter African American IBD Study (MAAIS) coordinated by Johns Hopkins IBD Genetics Research Center (GRC) of the NIDDK IBD Genetics Consortium (IBDGC) with recruitment from 13 collaborating IBD centers and 4 other IBDGC GRCs⁵, and additional AA control samples from the controls from rheumatoid arthritis (RA), systemic lupus erythematosus (SLE) and type 1 diabetes (T1D) Immunochip studies; (2) Emory: GENESIS AA cohort, an ancillary study of the NIDDK IBDGC, coordinated by Emory University with recruitment of IBD cases and matched controls from 12 of their collaborating IBD centers; and (3) Cedars: Cedars-Sinai Medical Center recruited IBD cases and controls with additional controls from the Pharmacogenetics and Risk of Cardiovascular disease Study Group (PARC) from San Francisco General Hospital and University of California, Los Angeles¹³.

All subjects gave informed consent to participate in genetics research studies in protocols approved by each sites institutional review board. Cases were confirmed as CD, UC, or IBD type undetermined (IBDU) in accordance with the NIDDK IBDGC phenotyping manual¹⁴. Details regarding controls are described in the *Supplement*. See *Acknowledgements* for listing of all recruitment centers.

Genotyping and Quality Control (QC)

DNA samples were derived from whole blood. All DNA samples were genotyped using the Immunochip³ and genotype determinations (allele calls) were made using GenomeStudio version 2011.1 and Genotyping Module Version 1.9.4. All MAAIS samples and the RA, SLE, and T1D controls were genotyped at Feinstein Institute for Medical Research. All Emory, Cedars-Sinai and PARC samples were genotyped at Cedars-Sinai Medical Center Genetics Institute.

Several SNP-wise and sample-wise quality filters were applied (*Supplementary Figure 1*). Samples were excluded if they had <99% data completeness, differed by >3 standard deviations from the mean heterozygosity for the study, had discrepant gender, or were unexpectedly the first-degree relative of any other sample in the study. Matching of cases and controls was done by determining principal components (PC) using the software EIGENSTRAT¹⁵, plotting PC1 against PC2, followed by visual inspection and elimination of outlier samples. Three successive rounds were necessary until a satisfactory matching of cases/controls (*Supplementary Figure 2*) was obtained.

Local and Global Ancestry Estimation

Because AAs are well-modeled as linear combinations of West African (YRI) and European (CEU) ancestries¹⁶, to estimate the locus-specific local ancestry, we chose the WINPOP model in LAMP package¹⁷ for its fast computation with low error rate¹⁸. Average West African (global YRI) ancestry was estimated by using ADMIXTURE¹⁹.

Study-wide Association and Admixture, and Replication of 163 SNPs Established in Caucasian ImmunoChip Study (CIS)

For all analyses, we compared three phenotypes, all IBD, CD, and UC, against the same set of AA controls. We performed association and admixture mapping both under generalized linear models. Sex, recruitment coordinating center (Hopkins, Emory or Cedars), GRC (Feinstein or Cedars), global YRI ancestry, and the first 10 PCs were included in multiple regression with IBD affection status, and those significantly associated with IBD were used as covariates in association and admixture mapping.

We estimated the testing burdens empirically by assessing the autocorrelation (of genotypes for association or local ancestry proportions for admixture) of all the SNPs on each autosomal chromosome for each individual, and then summing over the 22 chromosomes and averaging across individuals²⁰.

The testing burdens of independent SNPs or admixture regions, specific to our dataset, were 23,639.4 and 128.4 for association and admixture mapping respectively. Association peaks with $p < 2.1e-6$ (5% false positive rate corrected for number of independent SNPs, i.e. $0.05/23,639.4$) were marked as significant, while those with $2.1e-6 < p < 4.2e-5$ were marked as suggestive (i.e. one false positive per study-wide test burden). Admixture peaks with $p < 3.9e-4$ ($0.05/128.4$) were marked as significant.

For chromosomes with multiple significant/suggestive association SNPs, conditional regression was performed to determine number of independent signals. Specifically for m SNPs, all possible $m*(m-1)/2$ pairwise combinations were tested. For each pair if the target SNP remained significant in the presence of the conditional SNP then they are independent of each other; otherwise, they have arisen from the same signal.

To evaluate the 163 loci with reported genome-wide significance in the CIS, we tested the most statistically significant SNPs at each locus and present on the ImmunoChip (Maximal-CIS SNPs). Criteria for replication was $p < 3.1e-4$ ($0.05/163$).

Gene Ontology was utilized to functionally annotate the genes within each significant admixture region, using the PANTHER Classification System (<http://pantherdb.org>). Genes with immunological or gastrointestinal-relevant functions were considered to be suggestive candidate genes within the region.

eQTL Evaluation

For significant/suggestive association SNPs we also performed local (*cis*-) and distant (*trans*-) expression quantitative trait locus (eQTL) mapping with R package MatrixEQTL²¹ on peripheral blood mononuclear cells (PBMCs) drawn from a different set of 85 unrelated AA study subjects profiled with Illumina HumanHT-12 v4 Expression BeadChips and genotyped on Illumina HumanOmni1 or HumanOmni2.5 BeadChips²². We defined gene-SNP pairs within 1Mb of another as local, otherwise distant, and those with false discovery rate (FDR) <0.05 were considered significant.

Network Analysis

We first selected genes with association $p < 0.005$, and then the identified genes annotated with multiple biologically functional databases including Reactome²³, human protein reference databases (www.hprd.org), and NCI/Nature Pathway Interaction Database. The networks were then constructed from the known interactions in those databases. In addition, we identified the top KEGG pathways associated with each network using the enrichment analysis tool in STRING (<http://string-db.org/>). See *Supplement* for additional details.

Results

After QC measures were performed, 3,308 samples (1,511 IBD cases and 1,797 controls) and 130,241 unique autosomal SNPs remained for association and admixture analyses (*Supplementary Figures 1* and *2*). Average West African ancestry was higher in controls than cases ($81.7 \pm 9.7\%$ vs. $80.0 \pm 10.3\%$, $p < 1e-5$), and also differed by coordinating centers ($p < 1e-10$), with YRI proportion lowest for AAs from the American West Coast, similar to other genetic studies²⁴ (*Supplementary Table 1*).

Five variables were significantly associated with IBD ($p < 0.05$) and therefore were included as covariates for all subsequent analyses: sex ($p = 5e-7$), recruitment coordinating center ($p = 2e-5$), GRC ($p = 4e-4$), PC2 ($p = 0.015$), and global ancestry ($p = 0.03$). Quantile-quantile plots for association mappings and genomic inflation factors are shown in *Supplementary Figure 3*.

Replication of Maximal-CIS SNPs

152 of the 163 Maximal-CIS SNPs passed QC. The remaining 11 SNPs did not have any tagging ($r^2 < 0.6$) SNPs that could be used as alternative markers. Five SNPs met criteria for replication ($p < 3.1e-4$): rs5743289 that tags the three common *NOD2* mutations, rs11209026 that encodes the *IL23R* R381Q protective variant, rs1801274 that encodes the *FCGR2A* H167R risk variant, rs11742570 in the 5p13.1 gene desert near *PTGER4* and rs12946510 on 17q21 just 3' of *IKZF3* (Table 1).

For most of the 152 SNPs, the AA odds ratios are in the same direction as those from the CIS (correlation=0.78, Figure 1). 81 SNPs had AA ORs within the 95% CIS confidence intervals (CI), including one replicated SNP (rs11742570). Nominal levels of significance ($p < 0.05$ and same risk allele) were observed for 41 of the 152 (27%) variants (*Supplementary Table 2*).

Study-wide Association

Association results for IBD, CD and UC are shown in Figure 2 (*left panels*). Suggestive association for IBD was observed at the following 7 loci for 15 SNPs (Table 2): 1p at *IL23R*; 2p near the p-telomere and 4 Mb upstream of an associated locus in the CIS near *C2orf43*; 5p13.1 gene desert (5 SNPs in tight LD, pairwise r^2 ranging from 0.52 to 1.00); 5q 70kb telomeric of *IL12B* (2 SNPs in tight LD, $r^2=0.87$); and 17 in the *STAT5A/STAT3* region (6 SNPs in 3 LD blocks). Conditional regression revealed 3 independent signals from the latter region: three *STAT5A* SNPs (rs7220367, rs7217884 and rs13380828, all monomorphic in CEU, r^2 ranging from 0.46 to 0.99) in one block; two SNPs 200 kb apart (rs730086 in *KAT2A* and rs1053004 in *STAT3*, $r^2=0.44$); and rs7224339. IBD, being the phenotype with the largest sample size had greatest power to detect association evidence. However, 72% of cases had CD, and not surprisingly SNPs at 5p15.3 (*PTGER4*), *IL12B*, *KAT2A* and *STAT5A* also showed suggestive association for CD, with CD consistently showing greater association evidence at 5p15.3 than all IBD (Table 2).

For UC, the major peak located in the *HLA* region, with greatest association for rs9271366 ($p=7e-6$). Conditional analysis revealed that all suggestive *HLA* SNPs could be accounted for by rs9271366 (*Supplementary Figure 4*). Two SNPs showed suggestive associations on chromosome 3, at 13Mb and at 64Mb (near *HDAC11* and *LINC00994*), neither within 5Mb of any established IBD loci.

Raw genotyping intensities were visually examined for all replicated/suggestive SNPs and only rs35990859 (at *IL12B*) had sub-optimal cluster separation (data not shown).

Admixture Association

We observed four chromosomal regions of significant admixture association (Figure 2, *right panels* and Table 3) with all having significant evidence for both IBD and CD except for 16p12 (IBD-only). For all of these regions, CEU (European) ancestry increases risk and YRI (West African) ancestry was protective. Just below significance was an area with increased CD risk from CEU, maximal at rs2111112 ($p=4.9e-4$) and 3 Mb from *NOD2* (with increased CEU ALD extending through *NOD2*). Conditioning on *NOD2* genotype rs5743289 weakened this ALD evidence ($p=0.017$). A list of annotated genes with immune-related functions that map to each region is included in *Supplementary Table 3*.

eQTL Evaluation

We conducted PBMC eQTL mapping for 26 (5 significant replication and 21 suggestive study-wide association) SNPs with eQTL data. After controlling for multiple comparisons, 0 distant and 6 local gene-SNP pairs showed significant association (*Supplementary Table 4*): rs1053004 on chromosome 17 was associated with *KRT19* ($p=1.7e-4$) and with *TTC25*

($p=8.0e-4$) expression; 3 SNPs (rs1876141 [$p=5.5e-4$], rs6866402 [$p=7.5e-4$], and rs1505994 [$p=7.5e-4$] in tight LD ($r^2>0.99$) at 5p13.1 with *Complement Component 6 (C6)* expression; and rs1801274 with *CD84* expression ($p=1.2e-3$). *PTGER4* expression was evaluated but was not associated with any SNP evaluated ($p>0.05$).

Network Analysis

We found multiple networks demonstrating significant influence for IBD, CD and UC in AAs even after FDR and Bonferroni corrections (Table 4). Cytokine-cytokine receptor interaction was the dominant pathway for CD and IBD overall, but for UC was second in effect to Measles (which also played a significant but less prominent role in IBD and CD). Jak-STAT and Chemokine signaling pathways were included in top 3 networks for IBD and CD (and Jak-STAT alone for UC). In addition, T cell receptor signaling pathway was one of the top pathways in UC and IBD, but not CD.

Discussion

In this study of IBD genetics in the AA population, we assembled the largest set of cases and controls (more than 4 times larger than any prior AA IBD study and the first genetic study of AA UC), evaluated for replication the majority of established IBD associations and interrogated the majority of known IBD loci for novel associations, and performed pathway and eQTL analyses to further inform about the nature of AA IBD genetics. Although our genotyping platform (not being GWA) limited association mapping primarily to replicating known associations and interrogating established, immunologically related loci, we also used the more powerful method of MALD to identify novel loci throughout the autosomal genome and to complement the association mapping.

We replicated, using stringent criteria ($p<3.1e-4$), five CIS loci. As our study has more CD than UC cases, most of our replications were for CD. Not surprisingly we replicated loci with greater impact in other populations. Three of the five replications, *NOD2*, *IL23R* and 5p13.1, account for the greatest degree of CD variance estimated in CIS. The two other replicated loci also have relatively high OR for Caucasian IBD: *FCGR2A* and *IKZF3* (17th and 47th ranked ORs of the 163 CIS loci).

Two replicated CIS SNPs are more frequent in, and hence IBD risk is more likely to arise from, CEU than YRI genome: rs5743289 that tags the 3 common *NOD2* CD-associated mutations rs12946510 at *IKZF3* (Table 1). In contrast, the two other replicated SNPs, rs11742570 at 5p13.1 and the rs1801274 at *FCGR2A* with functional variant H167R, have similar presence in CEU and YRI genomes, whereas the R381Q wildtype albeit risk variant of *IL23R* at rs11209026 is more common in YRI than CEU genomes.

Given our sample size, we had 80% power to replicate Maximal-CIS SNPs with $OR>1.3$ and $MAF>0.2$. *Supplementary Figure 5* illustrates our power at different ORs/MAFs at three levels of significance. Although our study was underpowered a-priori for genome-wide association (and obtaining enough AA individuals for genetic studies, as statically powerful as those in Caucasians, may be impractical for years to come), we have identified SNPs in the AA population at a level of association for which to target for independent replication.

Two replicated loci also had additional SNPs with suggestive association: 5p13.1 and *IL23R*. At 5p13.1 rs4286721 showed greatest association with CD ($p=2.97e-6$), only marginally below study-wide significance ($p<2.1e-6$). The suggestive SNPs are in LD, are protective and more frequent in YRI than CEU, and, in our PBMC eQTL analysis, correlated with complement component 6 (*C6*) instead of *PTGER4*, the associated gene in the original discovery in lymphoblastoid cell lines²⁵. *C6* is a reasonable candidate gene, given that *C2* and other complement-related genes are associated with numerous IMDs. For rs7515029 at *IL23R* the protective allele is almost twice as frequent in YRI (9%) than CEU (5%) indicating another African-derived protective variant, in addition to the well-established R381Q replication.

Our strongest UC signal was in the *HLA* region, similar to that observed in all examined populations. The most significant SNP, rs9271366, known to tag the *HLA* class II allele DRB1*1502 in other populations, is the same SNP found most statistically significant in both Japanese²⁶ and Korean²⁷ UC GWASs ($p=1e-70$ and $p=1e-18$ respectively). Hence, our rs9271366 UC association ($p=7.47e-6$) is justified as replication of an established UC SNP. It also accounted for nearby associations according to conditional analysis (*Supplementary Figure 4*). Interestingly, it was found to be the most associated *HLA* SNP in AA SLE, a disease 4-fold more frequent in AAs than CAs²⁸.

The strongest IBD association was observed for rs730086, with OR=1.4 ($p=2.26e-6$, just below study-wide significance), at an intron of *KAT2A*, a histone acetyltransferase gene recently linked to repression of IFN-beta and innate antiviral immunity through inhibition of *TKB1*²⁹. In LD with rs730086 is rs1053004 ($r^2=0.44$), located in the 3' utr of *STAT3*, which is eQTL for two genes (FDR=0.038): *KRT19*, a gene that produces a major type 1 keratin expressed in ileal and colonic epithelium with a broad distribution in simple and stratified epithelia; and *TTC25*, a gene important for celiogenesis expressed in bone marrow but not in intestine. The risk variants are much more frequent in CEU than YRI.

We observed two other independent signals for IBD and CD on chromosome 17 centered about *STAT5A/STAT3* adjacent genes. These two signals are protective and African-specific (monomorphic in CEU). We found no association ($p>0.1$) for rs12942547, the CIS SNP located in *STAT3* intron with nearly identical frequencies in CEU and YRI. Complementing these findings is significant ALD that overlaps this chromosome 17 region (and extends through *IKZF3* and *STAT3*) with the CEU genome producing IBD risk and YRI being protective. Conditioning on the *IKZF3* replicated SNP (rs11742570) and the 3 independent *STAT5A/STAT3* associations eliminated this ALD ($p=0.8$). An important implication of our association and admixture results is that the common CEU *STAT5A/STAT3* haplotype likely contributes to IBD risk in the Caucasians – a finding made possible by studying an admixed population. Sequencing studies in AAs will be important to identify potential functional variants in LD with the YRI-specific protective alleles.

We found three other regions with significant ALD. Although ALD regions should be unbiased to known loci (as ImmunoChip contained AIMs throughout the genome) all four regions overlap CIS loci. The most highly associated region is on chromosome 10, includes the *IPMK/CISD1/UBE2D1/TFAM* locus and extends to within 800 kb of *ZNF365* (using a

genome-wide admixture $p=0.10$ cut-off). A region with ALD associated with CD and IBD on chromosome 15 contains *SMAD3*, a gene associated with need for multiple surgeries in CD³⁰. A region on chromosome 16 contains *PRKCB*, *IL4R* and *IL21R*, and extends centromeric just to *SBKI*. Each of the ALD regions contains additional potential candidate genes, as noted in Supplementary Table 3.

The top three KEGG pathways in AA IBD (cytokine, Jak-STAT and chemokines) were among the top four KEGG pathways found in CIS. However, not observed in AA IBD was the Leishmania infection pathway – second most significant pathway in the CIS; whereas AA UC, IBD, and CD all showed strong evidence for measles pathway and UC also showed significant evidence for African trypanosomiasis – both pathways not observed in CIS.

The high frequency of genes associated with infectious disease supports the hypothesis that IBD genetic susceptibility may be a by-product of evolutionary adaption to human pathogens. Hence the differential infectious disease pathways associated with AA and Caucasian IBD may be related to adaptation to geographically distinct infectious diseases. In total, these findings suggest that, while major pathways are similar across populations, some are distinct and may be targets for personalized IBD therapies.

This first, in-depth characterization of AA IBD genetics provides a basis to compare IBD genetics with Caucasian² and East Asian^{26,27,31-36} populations where multiple GWAS, replication and Immuchip studies have been performed (Figure 3). Five of the AA loci with suggestive/replication evidence are associated in all three populations: *IL23R*, *FCGR2A*, *IL12B*, *HLA* and *STAT5A/3*, with the functional SNPs for *IL23R* and *FCGR2A* the same. The higher OR loci tend to be observed in more than one population. The *STAT5A/STAT3* locus stands out in AAs: the ORs for the three independent associations are 0.76, 1.40 and 0.55, suggesting that this region likely has a stronger influence in AA than Caucasian IBD (OR=1.1 for rs12942547 in CIS). A Japanese CD GWAS found relatively strong influence for *STAT3*³³, maximal at rs9891119, but we found no evidence in AAs for this SNP equally frequent in YRI, CEU and East Asians.

In summary, our study reveals that in AAs *HLA* SNPs demonstrate the dominant signal for UC; *STAT5A/STAT3* shows disproportionate association with IBD and CD including novel African protective haplotypes and common European risk haplotypes that together with an *IKZF3* CD replication 3 Mb centromeric likely gives risk to significant chromosome 17 regional ALD. We identified three other chromosomal regions contributing significant IBD risk from European admixture. We replicated Maximal-CIS SNPs for *NOD2*, *IL23R*, 5p13.1, and *FCGR2A*, identified additional risk variants at 5p13.1 and *IL23R*. We observed a strong correlation in ORs for Maximal-CIS SNPs between our study and the CIS suggesting that additional Caucasian established loci likely play a role in AAs. We also demonstrated other known (*IL12B*) and novel (*C2orf43*, *HDAC11* and *LINC00994*) suggestive areas of association interest. The new suggestive associations will need to be validated by independent replication. Finally a network analysis showed that, as in other studies, cytokines, Jak-STAT signaling and chemokine pathways play major roles, but also suggests that measles and African trypanosomiasis pathways may be important for further investigation. This study has yielded vital information not only on the etiopathogenesis of

IBD specifically for AAs, but also about risk variants and ancestral chromosomal regions that may also contribute to IBD pathogenesis in Caucasians, as we continue our exploration of AA IBD genetics.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

ALD	admixture linkage disequilibrium
AAs	African Americans
AIMs	ancestry informative markers
CAs	Caucasian Americans
CIS	Caucasian Immunochip study
CD	Crohn's disease
CEU	European ancestry
eQTL	expression quantitative trait locus
FDR	false discovery rate
GRC	genetics research center
GWA	genome wide association

IMD	immune-mediated diseases
IBD	inflammatory bowel disease
IBDU	inflammatory bowel disease type undetermined
OR	odds ratio
PBMCs	peripheral blood mononuclear cells
QC	quality control
RA	rheumatoid arthritis
Maximal-CIS SNPs	the most statistically significant SNPs at each locus in the Caucasian ImmunoChip study and present on the ImmunoChip genotyping array
SLE	systemic lupus erythematosus
T1D	type 1 diabetes
UC	ulcerative colitis
YRI	West African ancestry

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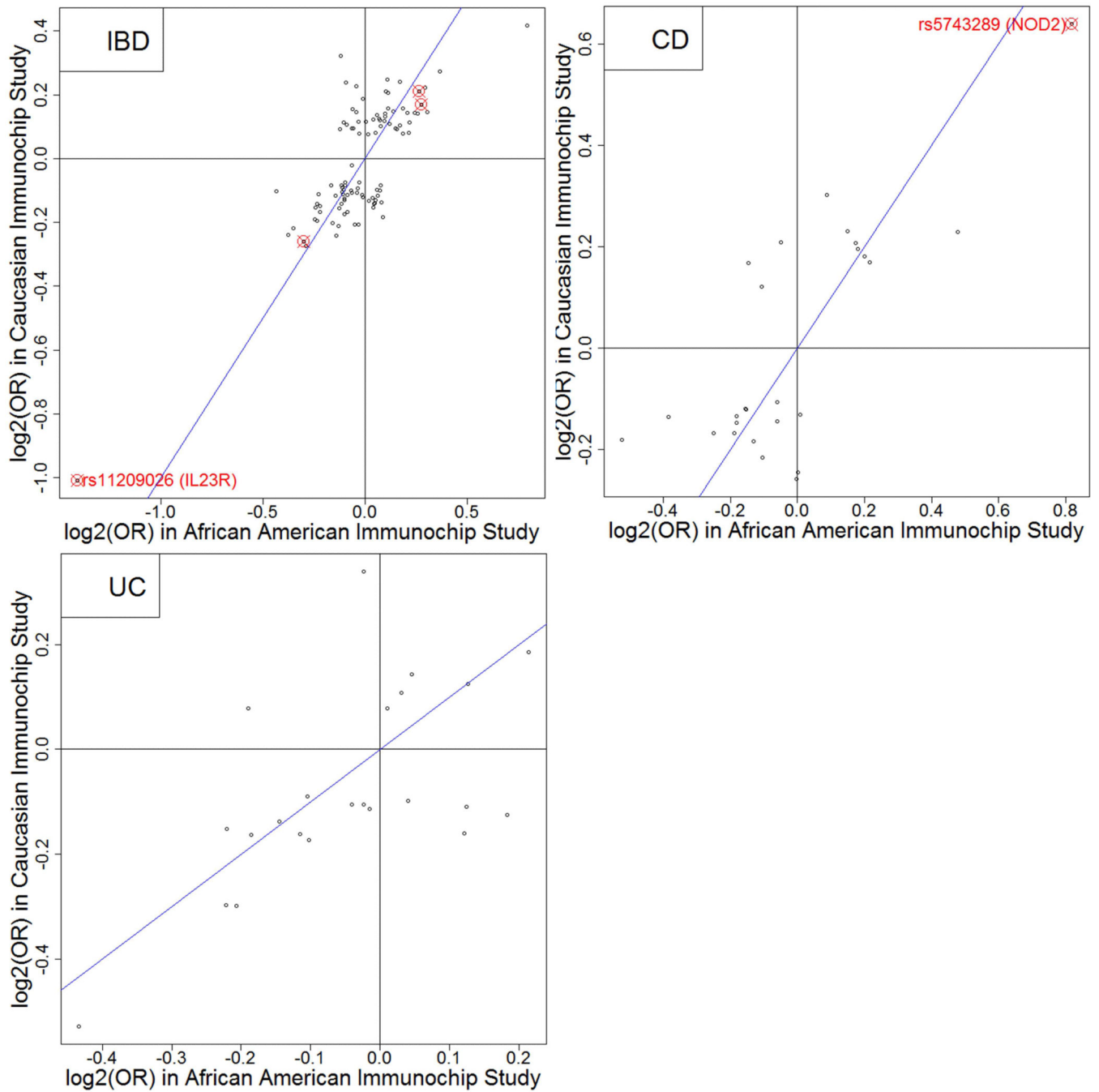


Figure 1.

Comparison of $\log_2(\text{Odds ratios})$ estimated in this study with those in *Caucasian ImmunoChip Study (CIS)* for 110 IBD-general (correlation=0.78), 26 CD-specific (correlation=0.77) and 23 UC-specific (correlation=0.61) *Maximal-CIS SNPs*.

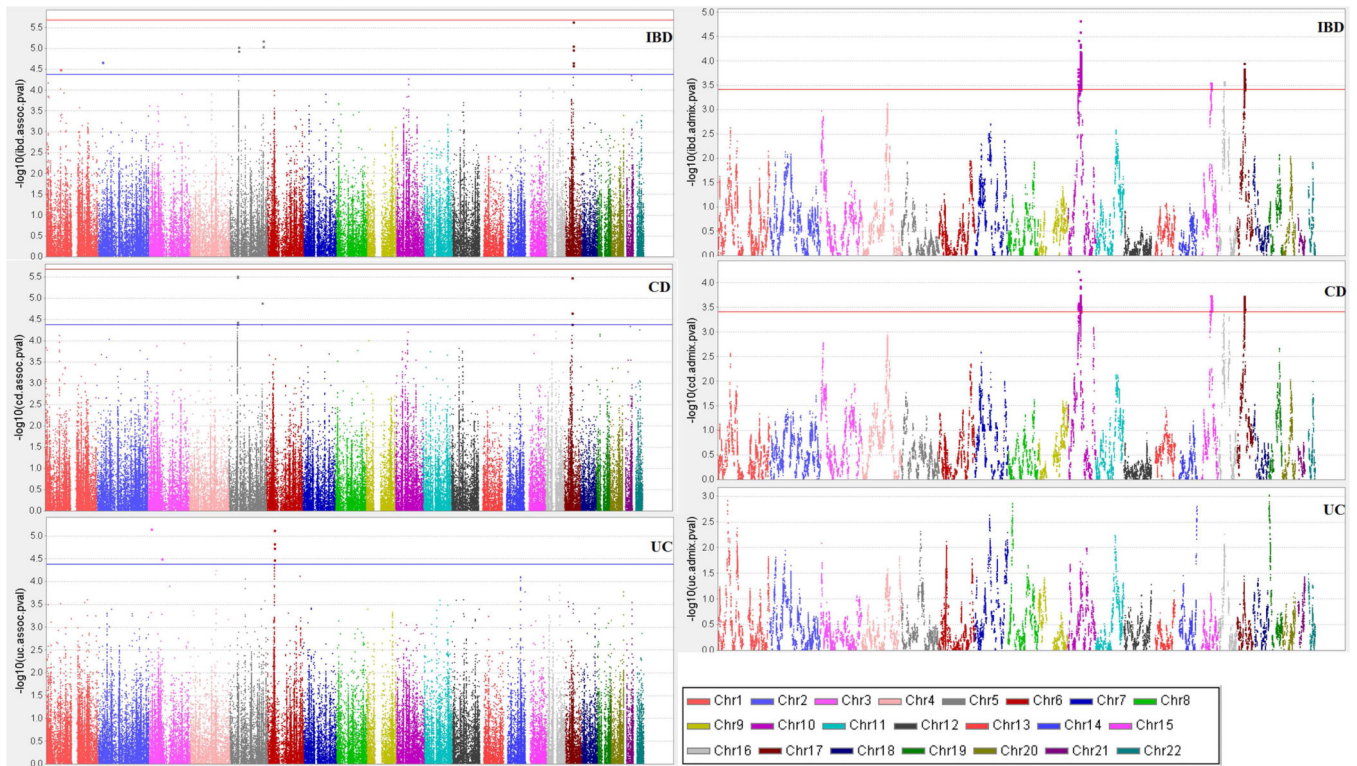
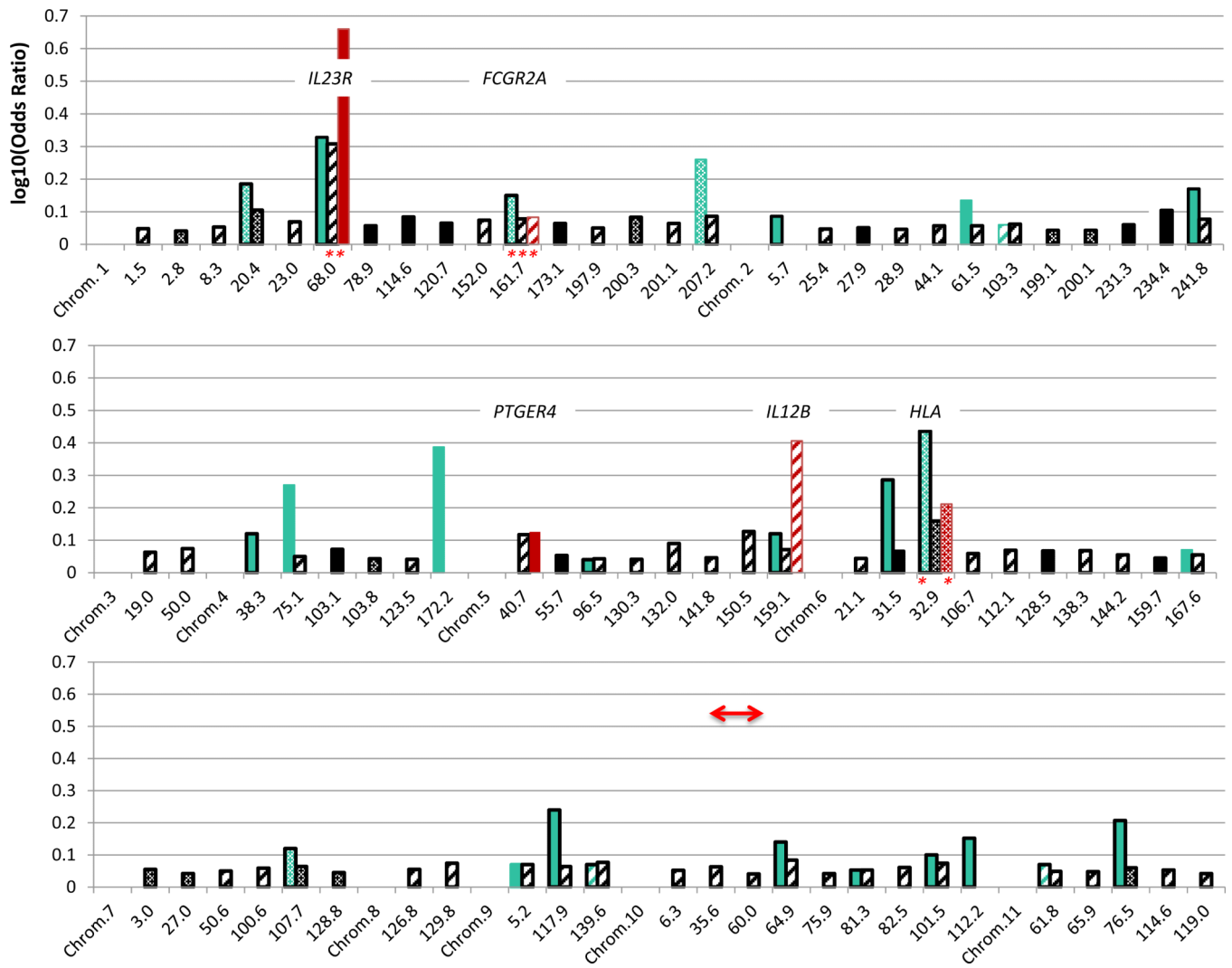


Figure 2. Association mapping (left) and admixture (right) mapping p-values (in $-\log_{10}$) for IBD (top panel), CD (middle panel) and UC (bottom panel).



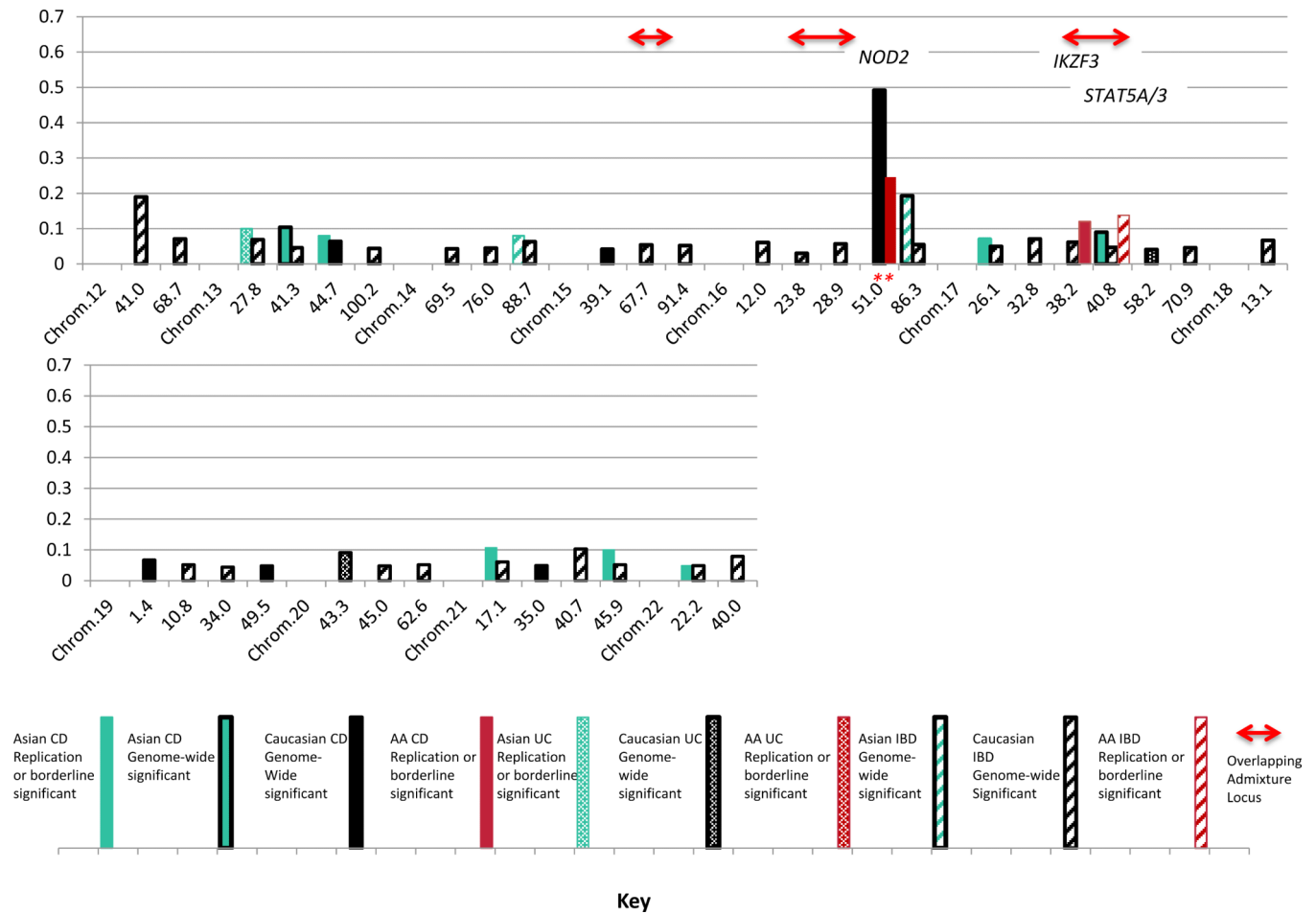


Figure 3. Comparison of $\log_{10}(\text{Odds Ratios})$ at the risk alleles by chromosomal position (in Mb, Genome Build 37) between Caucasian (*black*), East Asian (*green*) and African American (*red*) loci for IBD (*hatched*), CD (*solid*) and UC (*stippled*). Bars with *black outlines* represent loci with reported genome-wide significant association evidence in the CIS (*black*, limited to OR 1.1) or in East Asian studies (*green*). Bars *without outlines* are present for AA or East Asian replications (at $p < 3.1 \times 10^{-4}$) of CIS-Maximal SNPs, or for SNPs evaluated in these populations with *suggestive evidence for association* at established CIS loci ($p < 4.2 \times 10^{-5}$) or borderline of genome-wide significance for novel loci ($p < 1 \times 10^{-6}$). *Asterisks* denote the same associated SNPs in AA and additional populations. *Red arrows* denote overlaps between significant admixture regions and association loci.

Table 1

Significant association for replication ($p < 3.1 \times 10^{-4}$) for SNPs established in Caucasian Immunochip Study (CIS)

SNP	Chr	Mb ^c	Nearest Gene	A1 ^d	A2 ^d	YRI ^e	CEU ^e	Case ^e	Ctrl ^e	CIS ^e	Sig ^f	p ^f	OR ^f	L95CI ^f	U95CI ^f	CIS Sig ^g	CIS OR ^g	CIS L95CI ^g	CIS U95CI ^g
rs11209026 ^{a,h}	1p31.3	67.71	IL23R	A	G	0.009	0.041	0.007	0.014	0.067	CD	7.53E-05	0.219	0.103	0.464	IBD	0.497	0.465	0.531
rs1801274 ^a	1q23	161.48	FCGR2A	A	G	0.496	0.491	0.506	0.453	0.525	IBD	2.60E-04	1.211	1.093	1.343	UC	1.192	1.15	1.234
rs11742570 ^a	5p13.1	40.41	PTGER4	A	G	0.385	0.354	0.342	0.390	0.39	IBD	1.29E-04	0.812	0.729	0.903	CD	0.773	0.747	0.799
rs5743289 ^{b,h}	16q21	50.76	NOD2	A	G	0	0.226	0.052	0.032	0.178	CD	6.12E-05	1.763	1.336	2.326	CD	1.557	1.497	1.618
rs12946510 ^a	17q21	37.91	IKZF3	A	G	0.119	0.500	0.233	0.201	0.467	CD	9.31E-05	1.319	1.148	1.516	IBD	1.157	1.124	1.19

^a IBD-general SNP in CIS;

^b Crohn's disease-specific SNP in CIS;

^c SNP position in mega base-pair (Mb, Genome Build 37);

^d Minor (A1) and major (A2) allele in current dataset respectively;

^e Frequency corresponding to minor allele (A1) for Hapmap African samples (YRI), Hapmap European samples (CEU), current African American IBD case (Case) and control (Ctrl) samples, and Immunochip case/control samples used in CIS respectively;

^f Most significant phenotype (Sig), corresponding p-value (p), minor allele odds ratio (OR) with upper (U95CI) and lower (L95CI) 95% confidence interval.

^g The most significant phenotype (Sig) and the corresponding odds ratio (OR), lower (L95CI) and upper (U95CI) bounds for 95% confidence interval for odds ratio in CIS;

^h SNP without expression data available in eQTL evaluation.

Table 2

Suggestive Study-wide Association ($p < 4.2 \times 10^{-5}$)

SNP	Chr	MB ^a	A1 ^b	A2 ^b	YRI ^b	CEU ^b	Case ^b	Ctrl ^b	Nearest Gene	Location	Sig. ^c	p ^c	OR ^c	L95CI ^c	U95CI ^c
rs7515029 ^g	1	67.60	G	A	0.093	0.049	0.075	0.101	<i>IL23R</i>	intergenic	IBD	3.17E-05	0.670	0.555	0.809
rs3072 ^g	2	20.88	G	A	0.027	0.354	0.100	0.130	<i>C2orf43</i>	intergenic	IBD	2.15E-05	0.697	0.590	0.823
rs10043340 ^g	5	40.49	C	A	0.466	0.275	0.361	0.434	<i>PTGER4</i>	intergenic	CD ^d	3.25E-06	0.754	0.669	0.849
rs4286721	5	40.50	G	A	0.385	0.252	0.319	0.386	<i>PTGER4</i>	intergenic	CD ^d	2.97E-06	0.748	0.662	0.845
rs6866402	5	40.52	A	G	0.442	0.257	0.368	0.428	<i>PTGER4</i>	intergenic	CD ^d	4.05E-05	0.782	0.695	0.879
rs1876141	5	40.53	G	A	0.442	0.267	0.367	0.428	<i>PTGER4</i>	intergenic	CD ^d	4.00E-05	0.782	0.695	0.879
rs1505994	5	40.53	A	G	0.442	0.267	0.368	0.429	<i>PTGER4</i>	intergenic	CD ^d	3.65E-05	0.781	0.694	0.878
rs35990859 ^g	5	158.80	G	A	-	0.092 ^e	0.014	0.027	<i>IL12B</i>	intergenic	IBD ^d	6.62E-06	0.393	0.261	0.590
rs36048684 ^g	5	158.82	A	T	-	0.050 ^e	0.013	0.027	<i>IL12B</i>	intergenic	IBD ^d	9.04E-06	0.398	0.265	0.598
rs730086	17	40.27	G	A	0.097	0.664	0.238	0.177	<i>KAT2A</i>	intron	IBD ^d	2.26E-06	1.373	1.204	1.567
rs7220367	17	40.44	G	C	0.392	0	0.285	0.349	<i>STAT5A</i>	intergenic	CD	2.23E-05	0.758	0.667	0.862
rs7217884 ^g	17	40.45	G	A	0.270	0	0.211	0.267	<i>STAT5A</i>	intron	IBD ^d	2.21E-05	0.765	0.675	0.866
rs13380828 ^g	17	40.45	A	T	0.297	0	0.210	0.266	<i>STAT5A</i>	intron	IBD	2.57E-05	0.766	0.677	0.867
rs1053004	17	40.47	A	G	0.119 ^f	0.611	0.169	0.118	<i>STAT3</i>	utr-3	IBD	1.08E-05	1.409	1.209	1.641
rs7224339 ^g	17	40.49	A	G	0	0	0.033	0.058	<i>STAT3</i>	intron	IBD	8.76E-06	0.552	0.425	0.717
rs2655211	3	13.49	G	A	0.179	0.431	0.190	0.265	<i>HDAC11</i>	intergenic	UC	6.97E-06	0.619	0.503	0.763
rs254855	3	64.07	A	G	0.261	0.301	0.287	0.214	<i>LINC00994</i>	coding	UC	3.13E-05	1.491	1.235	1.799
rs2395178 ^g	6	32.41	C	G	0.533	0.602	0.415	0.500	<i>HLA-DRA</i>	intergenic	UC	1.49E-05	0.692	0.586	0.818
rs9270986 ^g	6	32.57	A	C	0.173	0.204	0.218	0.156	<i>HLA-DRB1</i>	intergenic	UC	1.85E-05	1.559	1.272	1.91
rs9271366 ^g	6	32.59	G	A	0.168	0.192	0.202	0.141	<i>HLA-DQA1</i>	intergenic	UC	7.47E-06	1.627	1.315	2.013
rs2097431 ^g	6	32.59	A	G	0.332	0.394	0.445	0.364	<i>HLA-DQA1</i>	intergenic	UC	3.34E-05	1.436	1.210	1.703

^a SNP position in mega base-pair (Mb, Genome Build 37);

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^bFrequency corresponding to minor allele (A1) for Hapmap African (YRI), Hapmap European (CEU), and current African American case (Case) and control (Ctrl) samples respectively;

^cThe most significant phenotype (Sig) and corresponding p-values (p), odds ratio (OR) with lower (L95CI) and upper (U95CI) bounds for 95% confidence intervals;

^dSNP with suggestive association ($p < 4.2 \times 10^{-5}$) for both IBD and CD;

^eMinor allele frequency (MAF) for samples from 1000 Genomes pilot 1 CEU low coverage panel;

^fMAF for samples from the human variation panel of African Americans;

^gSNP without expression data available in eQTL evaluation.

Table 3

Significant ($p < 3.9 \times 10^{-4}$) admixture association regions

Maximal SNP	Chromosomal ^a	Position ^a	Phenotype ^b	p ^b	OR ^b	L95CI ^b	U95CI ^b	Candidate Genes ^d
rs1684909	10q11.23-10q21.2	49.94-63.25	IBD ^c	1.47E-05	0.542	0.472	0.715	ZNF365, REEP3, MBL2
rs603439	15q22.2-15q23	62.76-70.75	CD ^c	1.80E-04	0.549	0.484	0.751	TRIP4, SMAD6, SMAD3, MAP2K1, IGDCC4, IGDCC3
rs1423086	16p12.2-16p12.1	21.74-28.39	IBD	2.67E-04	0.586	0.465	0.781	IL4R, IL2IR, SLC5A11, PRKCB, ITFGI
rs2227322	17q12-17q21.31	37.39-40.93	IBD ^c	1.10E-04	0.580	0.519	0.765	ORMDL3, CSF3, CCR7, Keratin cluster

^aWindow containing SNPs with suggestive admixture ($p < 7.8 \times 10^{-4}$) by chromosomal banding and physical positions in Mb (Genome Build 37).

^bThe most significant phenotype (Phenotype) and the corresponding: p-value (p); odds ratio with each additional African ancestry (YRI) allele (OR); lower (L95CI) and upper (U95CI) bounds for 95% confidence interval for YRI odds ratio.

^cSNP with significant admixture ($p < 3.9 \times 10^{-4}$) for both IBD and CD.

^dCandidate genes highlighted based on literature review of genes located in physical window.

Table 4

Significant KEGG pathways for IBD, CD and UC

Top KEGG Pathways	Phenotype ^a	Genes ^b	p-value ^c	FDR ^c	Bonferroni ^c
Cytokine-cytokine receptor interaction	IBD	12	1.55E-12	3.66E-10	3.66E-10
Jak-STAT signaling pathway	IBD	8	4.07E-09	4.82E-07	9.64E-07
Chemokine signaling pathway	IBD	8	1.59E-08	1.26E-06	3.77E-06
Measles	IBD	7	3.32E-08	1.97E-06	7.88E-06
Pathways in cancer	IBD	9	8.65E-08	4.10E-06	2.05E-05
T cell receptor signaling pathway	IBD	5	6.33E-06	2.50E-04	1.50E-03
Focal adhesion	IBD	6	9.10E-06	3.08E-04	2.16E-03
Gap junction	IBD	4	5.97E-05	1.77E-03	1.42E-02
Fc gamma R-mediated phagocytosis	IBD	4	7.47E-05	1.97E-03	1.77E-02
Vascular smooth muscle contraction	IBD	4	1.74E-04	4.13E-03	4.13E-02
Cytokine-cytokine receptor interaction	CD	18	3.11E-21	7.37E-19	7.37E-19
Chemokine signaling pathway	CD	10	4.13E-11	4.89E-09	9.79E-09
Jak-STAT signaling pathway	CD	9	2.29E-10	1.81E-08	5.42E-08
Measles	CD	6	1.15E-06	6.84E-05	2.74E-04
Pathways in cancer	CD	8	1.76E-06	8.32E-05	4.16E-04
Measles	UC	7	1.97E-09	4.67E-07	4.67E-07
Cytokine-cytokine receptor interaction	UC	8	1.03E-08	1.22E-06	2.43E-06
Jak-STAT signaling pathway	UC	6	2.05E-07	1.62E-05	4.87E-05
T cell receptor signaling pathway	UC	5	8.88E-07	5.26E-05	2.11E-04
African trypanosomiasis	UC	3	2.33E-05	1.11E-03	5.53E-03
NOD-like receptor signaling pathway	UC	3	1.15E-04	4.56E-03	2.74E-02
Adipocytokine signaling pathway	UC	3	1.88E-04	6.38E-03	4.47E-02

^a Associated phenotype;^b Number of genes in the pathway;^c Nominal p-value, false discovery rate (FDR), and Bonferroni-corrected p-value respectively.