Twenty-two genetic loci in COPD overlap with population-based lung function and pulmonary fibrosis


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Chronic obstructive pulmonary disease (COPD) is a leading cause of mortality worldwide\(^1\). We performed a genetic association study in 15,256 cases and 47,936 controls, with genotyping of select top results (P < 5x10\(^{-6}\)) in 9,498 cases and 9,748 controls. In the combined meta-analysis, we identified 22 loci at genome-wide significance, of which 15 have been associated with lung function in general population samples, and 4 (EEFSEC, DSP, MTCL1, and SFTP\(D\)) are novel. We noted 2 loci shared with pulmonary fibrosis (FAM13A and DSP) but with opposite risk alleles for COPD. None of our loci overlapped with genome-wide associations for asthma; however, one locus has been implicated in the joint susceptibility to asthma and obesity. We also identified genetic correlation between COPD and asthma. Our findings highlight novel loci, demonstrate the importance of specific lung function loci to COPD, and identify potential regions of genetic overlap between COPD and other respiratory diseases.

COPD is characterized by persistent and progressive airflow limitation diagnosed by lung function testing\(^1\). While cigarette smoking is the major risk factor, susceptibility is also influenced by genetics\(^2\)-\(^4\). We established the International COPD Genetics Consortium (ICGC) to coordinate efforts to find susceptibility loci\(^5\). We defined cases based on pre-bronchodilator evidence of moderate-to-severe airflow limitation by modified GOLD criteria\(^6\); controls had normal spirometry, and all analyses were adjusted for age and cigarette smoking (pack-years and smoking status). We performed a two-stage genome-wide association study (Figure 1). In Stage 1, we combined 26 cohorts (Supplemental Table S1) containing 63,192 individuals (15,256 COPD cases and 47,936 controls). We selected 79 loci with P < 5x10\(^{-6}\) and in analysis Stage 2, we tested them in the UK BiLEVE dataset (9,498 COPD cases and 9,748 controls) from the UK Biobank and performed an overall meta-analysis (Supplemental Table S3).

We identified 13 genome-wide significant (P < 5x10\(^{-8}\)) associations in Stage 1. Following the Stage 2 analysis, an additional 9 loci achieved genome-wide significance in the overall meta-
analysis (Table 1 and Figure 2). Of the 22 genome-wide significant loci described in our study, 9 have been previously described as genome- (or exome-) wide significant in studies of COPD4-10: HHIP, CHRNA5/15q25, HTR4, FAM13A, RIN3, TGFB2, GSTCD/NPNT, CYP2A6/19q13, and 16p11.2/IL27. An additional 8 loci: ADGRG6/GPR126, THSD4, ADAM19, TET2, CFDP1, AGER, ARMC2, and RARB have been previously described and replicated (Supplemental Table S4) in general population GWASs of two measures of lung function (FEV₁ and FEV₁/FVC) that are used in conjunction to diagnose COPD11-17. One locus near PID1 was previously associated with FEV₁/FVC, but had not replicated in those studies13,17. Four loci are newly being described as genome-wide significant in association with either COPD or lung function: EEFSEC, DSP, MTCL1, and SFTPD (Figure 3).

To explore the potential function and causal genes for our novel loci, in addition to using publicly available datasets and prioritization tools (Supplemental Table S7), we also examined a larger set of lung expression quantitative trait loci (eQTL) in 1038 subjects, including subjects with COPD18 (Supplemental Table S8). As eQTL are pervasive, we also attempted to determine whether our association signal co-localized19 with an eQTL signal in lung tissue (Supplemental Table S9). We found strong evidence of co-localization (posterior probability > 0.8) for DSP, a major protein of desmosomes required for epidermal integrity20, and MTCL1, important in epithelial-cell-specific microtubule stabilization21,22, and expressed in respiratory epithelial cells23. Variants in strong LD with our top MTCL1 variant rs647097 appear to have enhancer histone marks in fetal lung fibroblasts24,25. In contrast, we found no evidence of a strong eQTL signal or co-localization at our other two novel loci. At 3q21, EEFSEC is a potential candidate, as it is a paralog of TUFM, a top blood and lung eQTL gene for the 16p11.2/IL27 COPD susceptibility locus10, recently part of a novel COPD-related pathway involving NLRX126-28. At 10q22, pulmonary surfactant-associated protein D (SFTPD) is the most likely candidate, as it is highly expressed in pneumocytes23, and sftpd (-/-) mice develop pulmonary emphysema29. SFTPD has been explored as a COPD biomarker30, and while
rs721917 is not an eQTL, polymorphisms in \textit{SFTPD}, including rs721917, may lead to decreased surfactant protein D levels\cite{31}; though the association of SFTPD polymorphisms with COPD susceptibility have been inconsistent. Our analysis also led to some additional insights into other previously described loci. We found evidence of COPD association and eQTL statistical co-localization in lung tissue (posterior probability > 0.8) for \textit{THSD4}, \textit{HHIP}, \textit{AGER}, \textit{CHRNA3}, and \textit{RARB} (Supplemental Table S9). Additional data on eQTLs (Supplemental Table S8), cohort-specific associations at each locus (Supplemental Figures S1a-v), fine mapping (Supplemental text and Table S20), and other supportive analysis for previously described and novel loci can be found in the Supplemental Materials.

We noted that our top variant at \textit{DSP} (rs2076295) is also associated ($P = 1.1 \times 10^{-19}$) with pulmonary fibrosis\cite{32}. Recently, a re-sequencing study\cite{33} at this locus identified a second fibrosis-associated variant (rs2744371). In addition, we noted that one other variant associated with pulmonary fibrosis\cite{32} had nominal significance in our study ($\textit{FAM13A} \text{rs2609255}; P_{\text{fibrosis}} = 2.20 \times 10^{-11}, P_{\text{COPD}} = 1.9 \times 10^{-7}$). Notably, for all three of these variants, the fibrosis risk allele is protective for development of COPD. Emphysema, a key component of COPD, and pulmonary fibrosis are both smoking-related lung diseases that have both shared and opposing pathophysiology\cite{34-36}, though genetic loci with opposing effects have not been previously described. Additional investigation of \textit{DSP} and \textit{FAM13A} as a well as a more comprehensive assessment of the shared genetic architecture of COPD and pulmonary fibrosis may lead to insight into both disorders.

Because our analysis relied on a spirometric definition of COPD alone, we did not specifically exclude other causes of airway obstruction. Asthma, typically resulting in reversible airway obstruction, can overlap with COPD in adults\cite{37}. To define COPD, we used pre-bronchodilator spirometry, which was available across all cohorts, and we included at least moderately affected cases ($\text{FEV}_1 < 80\%$ predicted). We examined the top set of genome-wide significant results in a subset of our largest cohorts with both pre- and post-bronchodilator data and densely imputed
genotypes; overall, the effect sizes (mean difference = 0.001) and P values (mean log₁₀ P value difference = 0.18) were similar (Supplemental Table S8 and Supplemental Figures S3 and S4). In addition, a recent GWAS of FEV₁, FVC, and FEV₁/FVC did not find substantial differences including and excluding subjects with asthma⁴⁶. We examined COPD associations of genome-wide significant asthma loci from the NHGRI-EBI GWAS Catalog³⁸ and none of the genome-wide significant loci overlapped. We also compared our results to the GABRIEL asthma study³⁹ (Supplemental Tables S9 and S10). Only two genome-wide significant loci from either asthma or COPD showed nominal association (P < 0.05) with the other disease (1q31.3 asthma locus, P = 0.048 with COPD; 3q21.3 COPD locus, P = 0.026 with asthma). However, we note that the 16p11.2 (CCDC101) locus has been described in the joint susceptibility to asthma and obesity⁴⁰. COPD susceptibility is strongly related to cigarette smoking. Two of our loci (15q25 and 19q13) have been previously associated with smoking behavior⁴¹,⁴², though we found no additional evidence of overlap in genome-wide significant loci described in the NHGRI-EBI GWAS Catalog³⁸ and Tobacco and Genetics Consortium GWAS⁴² (Supplemental Tables S11-S13). In contrast to minimal overlap in genome-wide significant results with asthma and smoking, we discovered a significant overall genetic correlation of COPD with asthma (r_{genetic} = 0.38, P = 6.2x10⁻⁵) using LD score regression in our white subjects⁴³,⁴⁴. We also assessed genetic correlation with population-based lung function, pulmonary fibrosis, smoking behavior, and two common COPD comorbidities, coronary artery disease and osteoporosis. We identified significant correlation with lung function and two aspects of smoking behavior, but not with interstitial lung disease (Figure 4). This result could mean that our two overlapping loci for COPD and pulmonary fibrosis are not representative of a broader correlation; alternatively, it could reflect limitations of sample size or a mix of positive and negative genetic correlations. Our analysis of partitioned heritability identified COPD genetic association enrichment in fetal lung tissue (coefficient P = 3.5x10⁻⁷); other enrichment analyses also support lung tissue or lung cell types (Supplemental Materials, Results section).
Our study is, to our knowledge, the largest genome-wide association study of COPD cases to date and includes over 60,000 subjects (including 15,256 COPD cases) in our Stage 1 analysis. We chose to combine subjects of different ethnicities, hypothesizing that the benefit of shared risk factors across ethnicities would outweigh power loss due to heterogeneity. While methods have been developed that can more rigorously assess the degree of overlap and provide additional power in this setting, none of our non-white cohorts were sufficiently sized or powered for these analyses. COPD is also a highly heterogeneous disease; whether a more precise phenotypic definition would result in greater power is not clear. We used a staged study design and examined overall meta-analysis P-values to determine genome-wide significance. Thus, 9 loci (TET2, CFDPI, TGFB2, AGER, ARMC2, PID1, MTCL1, SFTPD, and CYP2A6) from our Stage 1 analysis, which only reached genome-wide significance in either the Stage 2 UK BiLEVE analysis or the overall meta-analysis, should be further replicated. Six of these 9 association signals are significant if we consider a conservative Bonferroni correction for the 79 variants tested in Stage 2. Further, 8 of these 9 variants become more significant from the Stage 1 analysis to the overall meta-analysis, with the exception of RARB, which has a previously reported association with both lung function and airflow obstruction (Table 1).

The majority of our significant loci overlap with lung function loci, strengthening the foundation for investigating the relationship of lung function variability in the general population to risk of developing COPD. These loci are unlikely to reflect susceptibility for asthma or for cigarette smoking; however, our association as a whole shows evidence of shared heritability with asthma (supporting investigation into shared genetic etiologies for these diseases) and cigarette smoking behavior (despite adjustment for smoking in our statistical model). We identified enrichment for fetal lung cells, supporting a role for early life events contributing to future risk of COPD. Finally, we identify two loci that overlap with pulmonary fibrosis, but with opposite risk alleles. Our study highlights the important contribution of genetic association studies to understanding COPD, not
only by identifying novel loci, but also illustrating relationships with other pulmonary traits and diseases.
Online Methods

Study Cohorts

We invited investigators from 22 studies with genome-wide association data and COPD case-control or general population samples with spirometry to participate in a genome-wide association meta-analysis. Additionally, we included four cohorts with Illumina HumanExome v1.2 and custom genotyping based primarily on prior top results from a previously published COPD GWAS, using results with \( P < 1 \times 10^{-4} \) using plink ‘--clump’ on the COPDGene non-Hispanic whites to perform linkage disequilibrium pruning (\( r^2 < 0.8 \)), preferentially retaining both an imputed and genotyped top SNP at each locus. An additional group of variants was a candidate panel, based on results from a previous candidate gene analysis, as well as variants identified in association with lung function (supplementing the existing content on the array, which included variants from previous genome-wide association studies), including the lead SNP and a 200kb region around that SNP pruned for variants with \( P < 0.01 \) and \( r^2 < 0.8 \), and additional top-ranked SNPs for COPDGene-specific analyses for lung function, bronchodilator responsiveness, exacerbations, and SNPs from candidate genes.

The baseline characteristics of these 26 cohorts can be seen in Supplemental Table S1. Each cohort obtained approval from appropriate ethical/regulatory bodies; informed consent was obtained for all individuals. (Further cohort-specific methods can be found in the Data Supplement.) As most of these cohorts did not have post-bronchodilator spirometry, we used a modified definition of GOLD criteria based on pre-bronchodilator spirometry: forced expiratory volume in 1 second (FEV\(_1\)) < 80% and FEV\(_1\)/FVC ratio of < 0.7 for cases, and FEV\(_1\) > 80% and FEV\(_1\)/FVC > 0.7 for controls. Logistic regression was performed in each cohort, adjusting for age, sex, pack-years of smoking, ever-smoking status, current-smoking status, and ancestry-based principal components, as appropriate for each study. Summary statistics were
assessed using EasyQC\textsuperscript{47} version 10.1. More detailed cohort information, including cohort-specific methods, can be found in the Data Supplement.

**Genome-wide association quality control**

Summary statistics, including effect allele and other allele oriented to the + strand, effect allele frequency, chromosome and position (hg19), and imputation quality were uploaded to a secure site at the Brigham and Women’s Hospital / Channing Division of Network Medicine. Quality control assessments included assessing allele frequencies versus 1000 Genomes reference, standard error versus sample size, and quantile-quantile plots. Variants with an imputation quality metric of < 0.3 (provided a higher threshold for imputation quality was not already implemented), a minor allele count (MAC) of < 20 using the effective sample size or the number of cases and adjusted for imputation quality where applicable, were set to missing. Variants were included for meta-analysis if they were present in at least 13 studies (those with European ancestry and at least 7 million markers passing all quality control filters).

**Staged GWAS meta-analysis**

In Stage 1 of the analysis, we used Metal\textsuperscript{48,49} version 2011-03-25 to perform a fixed-effects meta-analysis of genome-wide data from 22 studies and four additional COPD cohorts genotyped on an Illumina HumanExome v1.2 platform with custom content; this content included a set of COPD candidate genes and regions identified from prior COPD GWAS efforts\textsuperscript{4}. We adjusted for inflation using genomic control correction in each study. We included study populations with subjects of non-European ancestry in the overall analysis, and additionally examined results limited to study populations of European ancestry. To identify variants to test for association in Stage 2 in the UK BiLEVE study, we selected top results (P < 5x10\textsuperscript{-6}) from the Stage 1 meta-analysis. We selected one lead variant from the chromosome 15q25, *FAM13*, and *HHIP* regions, as all of these have been described in multiple COPD GWASs\textsuperscript{4,7,8,15}. For the remainder of the regions, we performed linkage disequilibrium pruning using the plink2 --clump procedure with an $r^2$ of 0.5, additionally
examining these SNPs for the number of cohorts with passing quality control at each variant and including SNPs in strong LD (i.e., part of the same clump) with a lower degree of missingness. To identify independent results, we used GCTA-COJO\textsuperscript{50,51} on the Stage 1 meta-analysis for variants with $P < 5 \times 10^{-6}$ using the default distance of 10Mb. We used the COPDGene non-Hispanic whites (as the largest representative population) as the reference population for these analyses. An overall meta-analysis across the Stage 1 and Stage 2 (UK BiLEVE) cohorts was performed and variants with $P < 5 \times 10^{-8}$ were considered genome-wide significant (Figure 1).

**Lung eQTL analysis**

Lung expression quantitative trait loci (eQTL) were calculated from 1,111 human subjects who underwent lung surgery at three academic sites, Laval University, University of British Columbia (UBC), and University of Groningen, henceforth referred to as Laval, UBC, and Groningen, respectively. This lung eQTL dataset has been described previously\textsuperscript{18,52}. Briefly, 66.7\% to 91.2\% of the individuals in this study were current or former smokers and 24.2\% to 35.3\% had moderate to severe COPD (GOLD spirometry grade 2 to 4). Whole-genome gene expression profiling in the lung was performed on a custom Affymetrix array (GPL10379). Microarray pre-processing and quality controls were described previously\textsuperscript{18,53,54}. Probe sequences were mapped to the human genome (hg19) using Bowtie\textsuperscript{55} and probes not mapping to a coding region or having a common SNP (MAF $\geq$ 5\%) in their sequence were removed. Expression data were adjusted for age, sex, and smoking status using residuals obtained with the robust fitting of linear models function (rlm) in the R statistical package MASS. Residual values deviating from the median by more than three standard deviations were filtered as outliers. Genotyping was carried on the Illumina Human 1M-Duo BeadChip array.

Twenty-one out of the 22 SNPs (in main manuscript Table 1) were genotyped or imputed in the three cohorts, i.e. Laval, UBC, and Groningen. One of the SNPs, rs7186831, was not well-imputed; a proxy, rs11865296 in modest linkage disequilibrium ($r^2 = 0.54$, 1000 genomes phase 3,
EUR) was used instead. These variants were tested for association with adjusted expression traits (43,465 probe sets) in the lung. SNPs within 1 Mb up and downstream of the transcription probe set were considered as local-eQTL. Distant-acting eQTLs were further than 1 Mb away or on a different chromosome. Association tests were carried with PLINK1.956,57 in each cohort and then meta-analyzed using Fisher’s method. All local eQTL with nominal P value < 0.05 in the meta-analysis were considered. To provide an additional overall estimate of eQTL significance, we considered a Bonferroni correction threshold ([0.05/(22 SNPs x 43,465 probe sets) = P value < 5.2 x 10^{-8}]). Statistical analyses were performed in R3.2.358.

**Co-localization Analysis**

Co-localization of statistical signals between COPD genetic association and eQTL were examined using the coloc R package19. We used phenotypic summary statistics from whites with genome-wide association data and all eQTL results and examined 500kb flanks around the top 22 genome-wide significant associations found in the overall meta-analysis (Table 1).

**Sensitivity Analysis**

To estimate the effect of using pre- instead of post-bronchodilator lung function on our results, we examined the top set of genome-wide significant results in our largest cohorts with both pre- and post-bronchodilator data and densely imputed genotypes (COPDGene NHW and AA, ECLIPSE, NETT-NAS, and Norway / GenKOLS). Since subjects from these cohorts (except for COPDGene) were included based on post-bronchodilator values, including all subjects with COPD based on post-bronchodilator spirometry would lead to larger sample sizes and make comparison of P-values more difficult. Thus, we chose a random sample of post-bronchodilator cases and controls that matched the number of pre-bronchodilator cases and controls. We performed logistic regression using these equal sized set of pre- and post-bronchodilator cohorts, and meta-analyzed the results.

**Asthma overlap analysis**
We assessed the overlap between our results and known asthma susceptibility loci. We downloaded information on genome-wide significant (P < 5x10^{-8}) associations with asthma and asthma-related traits in the NHGRI-EBI GWAS Catalog, focusing on association studies with subjects of European ancestry. We assessed the association statistics of these reported asthma loci in our Stage 1 meta-analysis results. We also examined the asthma association statistics of our top COPD loci from overall meta-analysis using publically available asthma GWAS data from the GABRIEL Consortium. For COPD loci not present in the GABRIEL Consortium asthma GWAS data, we attempted to examine proxy SNPs in LD (r^2 > 0.5, 1000 genomes phase 1 CEU) with our top COPD loci.

To examine the genetic correlation of COPD and asthma over the entire genome, we performed LD score regression using summary statistics from publically available asthma GWAS data from the GABRIEL Consortium. For all comparisons using LD score regression, we filtered to HapMap3 variants, limited to white subjects with genome-wide data, and filtered on missingness using default parameters in munge_sumstats.py. For the GABRIEL data, we required a variant to be present in at least 35 of the studies.

Smoking behavior overlap analysis

We downloaded information on genome-wide significant (P < 5x10^{-8}) associations with the traits “nicotine dependence” and “smoking behaviour” in the NHGRI-EBI GWAS Catalog. We assessed these top smoking-associated SNPs in our Stage 1 meta-analysis results. We also assessed overlap of smoking and COPD in the publically available summary statistics from the 2010 Tobacco and Genetics Consortium GWAS. We evaluated our top COPD loci associations from overall meta-analysis with both cigarettes per day and ever-smoking traits. For COPD risk SNPs not directly analyzed in the Tobacco and Genetics Consortium GWAS, we attempted to examine proxy SNPs in LD (r^2 > 0.5, 1000 genomes phase1 CEU) with our top COPD loci.
To examine the genetic correlation of COPD and smoking behaviours (cigarettes per day and ever-smoking status) over the entire genome, we performed LD score regression using summary statistics from our current COPD study as noted above and publically available summary statistics from the 2010 Tobacco and Genetics Consortium GWAS.
Table 1. Overall study results showing 22 loci with genome-wide significant P values in overall meta-analysis following UK BiLEVE Stage 2 analysis.

<table>
<thead>
<tr>
<th>rsID</th>
<th>Closest Gene</th>
<th>Locus</th>
<th>Risk Allele</th>
<th>Alt Allele</th>
<th>Risk Allele Mean Freq (Range)</th>
<th>Stage 1 OR (95% CI)</th>
<th>Stage 1 P Value</th>
<th>UK BiLEVE (Stage 2) OR (95% CI)</th>
<th>UK BiLEVE (Stage 2) P Value</th>
<th>Overall Meta-Analysis P Value</th>
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<td>rs13141641</td>
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<td>1.224 (1.177-1.273)</td>
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<td>1.108 (1.051-1.169)</td>
<td>1.85E-04</td>
<td>4.96E-14</td>
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<tr>
<td>rs113897301</td>
<td>ADAM19</td>
<td>5q33.3</td>
<td>AT</td>
<td>A</td>
<td>0.175 (0.052-0.187)</td>
<td>1.195 (1.13-1.263)</td>
<td>4.52E-10</td>
<td>1.127 (1.066-1.192)</td>
<td>2.79E-05</td>
<td>1.58E-13</td>
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<tr>
<td>rs2047409</td>
<td>TET2</td>
<td>4q24</td>
<td>A</td>
<td>G</td>
<td>0.618 (0.222-0.649)</td>
<td>1.101 (1.059-1.146)</td>
<td>1.58E-06</td>
<td>1.136 (1.087-1.188)</td>
<td>1.95E-08</td>
<td>2.46E-13†</td>
</tr>
<tr>
<td>rs2955083</td>
<td>EEFSEC</td>
<td>3q21.3</td>
<td>A</td>
<td>T</td>
<td>0.881 (0.854-0.893)</td>
<td>1.195 (1.123-1.272)</td>
<td>2.00E-08</td>
<td>1.167 (1.093-1.246)</td>
<td>4.01E-06</td>
<td>4.16E-13</td>
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<tr>
<td>rs7186831</td>
<td>CFDP1</td>
<td>16q23.1</td>
<td>A</td>
<td>G</td>
<td>0.435 (0.226-0.472)</td>
<td>1.125 (1.071-1.183)</td>
<td>3.54E-06</td>
<td>1.116 (1.069-1.165)</td>
<td>6.63E-07</td>
<td>1.12E-11‡</td>
</tr>
<tr>
<td>rs10429950</td>
<td>TGF2B</td>
<td>1q41</td>
<td>T</td>
<td>C</td>
<td>0.731 (0.216-0.773)</td>
<td>1.117 (1.071-1.164)</td>
<td>1.83E-07</td>
<td>1.096 (1.044-1.15)</td>
<td>1.94E-04</td>
<td>1.66E-10†</td>
</tr>
<tr>
<td>rs2070600</td>
<td>AGER</td>
<td>6p21.32</td>
<td>C</td>
<td>T</td>
<td>0.955 (0.85-0.987)</td>
<td>1.276 (1.151-1.414)</td>
<td>3.54E-06</td>
<td>1.208 (1.105-1.319)</td>
<td>2.96E-05</td>
<td>5.94E-10‡</td>
</tr>
<tr>
<td>rs17707300</td>
<td>CDC101</td>
<td>16p11.2</td>
<td>C</td>
<td>T</td>
<td>0.373 (0.109-0.433)</td>
<td>1.122 (1.079-1.167)</td>
<td>6.24E-09</td>
<td>1.063 (1.018-1.111)</td>
<td>6.10E-03</td>
<td>6.75E-10</td>
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<tr>
<td>rs2806356</td>
<td>ARMC2</td>
<td>6q21</td>
<td>C</td>
<td>T</td>
<td>0.184 (0.052-0.242)</td>
<td>1.125 (1.071-1.181)</td>
<td>2.84E-06</td>
<td>1.116 (1.057-1.178)</td>
<td>6.85E-08</td>
<td>8.34E-10‡</td>
</tr>
<tr>
<td>rs16825267</td>
<td>PID1</td>
<td>2q36.3</td>
<td>C</td>
<td>G</td>
<td>0.929 (0.874-0.942)</td>
<td>1.242 (1.149-1.342)</td>
<td>5.22E-08</td>
<td>1.131 (1.045-1.224)</td>
<td>2.27E-03</td>
<td>1.68E-09†</td>
</tr>
<tr>
<td>rs2076295</td>
<td>DSP</td>
<td>6p24.3</td>
<td>T</td>
<td>G</td>
<td>0.554 (0.442-0.581)</td>
<td>1.107 (1.067-1.149)</td>
<td>4.95E-08</td>
<td>1.061 (1.016-1.107)</td>
<td>7.45E-03</td>
<td>3.97E-09</td>
</tr>
<tr>
<td>rs647097</td>
<td>MTCL1</td>
<td>18p11.22</td>
<td>C</td>
<td>T</td>
<td>0.269 (0.259-0.399)</td>
<td>1.106 (1.06-1.154)</td>
<td>3.03E-06</td>
<td>1.089 (1.038-1.142)</td>
<td>4.66E-04</td>
<td>6.14E-09†</td>
</tr>
<tr>
<td>rs1529672</td>
<td>RARB</td>
<td>3p24.2</td>
<td>C</td>
<td>A</td>
<td>0.831 (0.675-0.862)</td>
<td>1.162 (1.106-1.221)</td>
<td>2.37E-09</td>
<td>1.048 (0.991-1.109)</td>
<td>9.95E-02</td>
<td>2.47E-08</td>
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<tr>
<td>rs721917</td>
<td>SFTPD</td>
<td>1q22.3</td>
<td>G</td>
<td>A</td>
<td>0.422 (0.392-0.631)</td>
<td>1.092 (1.053-1.132)</td>
<td>2.11E-06</td>
<td>1.068 (1.023-1.115)</td>
<td>2.60E-03</td>
<td>2.49E-08‡</td>
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<tr>
<td>rs12459249</td>
<td>CYP2A6</td>
<td>19q13.2</td>
<td>C</td>
<td>T</td>
<td>0.662 (0.617-0.702)</td>
<td>1.126 (1.071-1.183)</td>
<td>2.89E-06</td>
<td>1.077 (1.029-1.127)</td>
<td>1.35E-03</td>
<td>3.42E-08*</td>
</tr>
</tbody>
</table>

OR = odds ratio, CI = confidence interval. *Genome-wide significant in overall analysis only †Stage 2 results significant after Bonferroni.
**Figure 1.** Study design showing cohorts used in each stage of the analysis.

**Stage 1:**
26 studies represented. European ancestry studies are shaded.

<table>
<thead>
<tr>
<th>Study</th>
<th>COPD Cases</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIC</td>
<td>1060</td>
<td>6164</td>
</tr>
<tr>
<td>BS8</td>
<td>205</td>
<td>3665</td>
</tr>
<tr>
<td>CHS EA</td>
<td>736</td>
<td>1586</td>
</tr>
<tr>
<td>COPACETIC</td>
<td>397</td>
<td>1906</td>
</tr>
<tr>
<td>COPDGene NHW</td>
<td>3068</td>
<td>2110</td>
</tr>
<tr>
<td>ECLIPSE</td>
<td>1741</td>
<td>149</td>
</tr>
<tr>
<td>EOCOPD*</td>
<td>394</td>
<td>495</td>
</tr>
<tr>
<td>ICGN*</td>
<td>1852</td>
<td>557</td>
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<tr>
<td>EQTL</td>
<td>252</td>
<td>224</td>
</tr>
<tr>
<td>FHS</td>
<td>701</td>
<td>5110</td>
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<tr>
<td>LifeLines</td>
<td>466</td>
<td>9863</td>
</tr>
<tr>
<td>Lovelace</td>
<td>259</td>
<td>641</td>
</tr>
<tr>
<td>MESA Caucasian</td>
<td>167</td>
<td>754</td>
</tr>
<tr>
<td>NETT-NAS</td>
<td>376</td>
<td>435</td>
</tr>
<tr>
<td>Norway/GenKOLS</td>
<td>846</td>
<td>695</td>
</tr>
<tr>
<td>RS1</td>
<td>112</td>
<td>815</td>
</tr>
<tr>
<td>RS2</td>
<td>94</td>
<td>811</td>
</tr>
<tr>
<td>RS3</td>
<td>106</td>
<td>1596</td>
</tr>
<tr>
<td>SPIROMICS</td>
<td>571</td>
<td>175</td>
</tr>
<tr>
<td>TCGS-Poland *</td>
<td>307</td>
<td>311</td>
</tr>
<tr>
<td>CHS AA</td>
<td>138</td>
<td>292</td>
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<tr>
<td>COPDGene AA</td>
<td>910</td>
<td>1556</td>
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<td>KARE</td>
<td>199</td>
<td>6741</td>
</tr>
<tr>
<td>MESA AA</td>
<td>94</td>
<td>532</td>
</tr>
<tr>
<td>MESA Hispanic</td>
<td>52</td>
<td>548</td>
</tr>
<tr>
<td>TCGS-Korea *</td>
<td>153</td>
<td>205</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>15256</strong></td>
<td><strong>47936</strong></td>
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</table>

**Stage 2:**
Top results from Stage 1 analysis tested in UK BiLEVE study.

<table>
<thead>
<tr>
<th>Study</th>
<th>COPD Cases</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK BiLEVE Never Smokers</td>
<td>3737</td>
<td>4871</td>
</tr>
<tr>
<td>UK BiLEVE Heavy Smokers</td>
<td>5761</td>
<td>4877</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>9498</strong></td>
<td><strong>9748</strong></td>
</tr>
</tbody>
</table>

Figure 2. P values for Stage 1 analysis (small open diamonds) with overlay of overall meta-analysis P values for SNPs analyzed in UK BiLEVE Stage 2 analysis (filled circles). Gene names in gray are previously described COPD or lung function (FEV₁ or FEV₁/FVC) loci; black are novel loci discovered in this study. The Stage 1 cohorts with available genotyping data (Supplemental Figures S1a-v) and the UK BiLEVE cohort determined the sample size for each top variant.
**Figure 3a-d. Regional association for novel loci.** LocusZoom plots showing regional association of variants at the four novel COPD loci. The point size is proportional to the sample size, where Stage 1 cohorts with available genotyping data (Supplemental Figures S1a-v) and the UK BiLEVE cohort determined the sample size for each top variant.
Figure 4 Genetic correlation (using LD score regression) between COPD and other traits. Shading represents strength of correlation, numbers represents unadjusted P-values. * indicates nominal (0.05) significance, ** indicates significant after Bonferroni correction for number of pairwise comparisons. fev1fvc and fev1 = lung function (FEV1/FVC ratio and FEV1 from CHARGE/SpiroMeta,13, ild = pulmonary fibrosis from Fingerlin et al.32,59, bilSmk = subset of smokers in the UK BiLEVE study16, smkCpd = cigarettes per day smoking from the Tobacco and Genetics (TAG) Consortium42, smkFormer = current versus former smokers from TAG, smkOnset = age of smoking initiation from TAG, smkEver = ever versus never smoking from TAG. cad = coronary artery disease from the CARDIoGRAM study60, height61 and bmi (body mass index)62 from the GIANT consortium, bmdLumbar and bmdFemoral = lumbar and femoral bone mineral density, respectively, from the Genetic Factors for Osteoporosis (GeFOS) Consortium63.
Author Contributions:

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Acknowledgments:
Please refer to the Supplement for full acknowledgements.

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B.P. serves on the DSMB of a clinical trial funded by the manufacturer and on the Steering Committee of the Yale Open Data Access Project funded by Johnson & Johnson.
N.L. and R.T-S. are shareholders and employees of GSK.
S.I.R. is a current employee and shareholder at AstraZeneca. He has served as a consultant, participated in advisory boards, received honorarium for speaking or grant support from: American Board of Internal Medicine, Advantage Healthcare, Almirall, American Thoracic Society, AstraZeneca, Baxter, Boehringer Ingelheim, Chiesi, ClearView Healthcare, Cleveland Clinic, Complete Medical Group, CSL, Daiichi Sankyo, Decision Resources, Forest, Gerson Lehman, Grifols, GroupH, Guidepoint Global, Haymarket, Huron Consulting, Inthought, Johnson and Johnson, Methodist Health System – Dallas, NCI Consulting, Novartis, Pearl, Penn Technology, Pfizer, PlanningShop, PSL FirstWord, Qwessential, Takeda, Theron and WebMD.
J.C.L. is currently an employee of GNS Healthcare in Cambridge, MA.
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P.G.W. has consulted for Amgen, Sanofi, Novartis, Genentech/Roche, Boehringer-Ingeleim, NeoStem and has had research grants from Pfizer and Genentech.
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