ORIGINAL ARTICLE
A common biological basis of obesity and nicotine addiction

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Smoking influences body weight such that smokers weigh less than non-smokers and smoking cessation often leads to weight increase. The relationship between body weight and smoking is partly explained by the effect of nicotine on appetite and metabolism. However, the brain reward system is involved in the control of the intake of both food and tobacco. We evaluated the effect of single-nucleotide polymorphisms (SNPs) affecting body mass index (BMI) on smoking behavior, and tested the 32 SNPs identified in a meta-analysis for association with two smoking phenotypes, smoking initiation (SI) and the number of cigarettes smoked per day (CPD) in an Icelandic sample (N = 34,216 smokers). Combined according to their effect on BMI, the SNPs correlate with both SI (r = 0.019, P = 0.00054) and CPD (r = 0.032, P = 8.0 × 10−7). These findings replicate in a second large data set (N = 127,274, thereof 76,242 smokers) for both SI (P = 1.2 × 10−5) and CPD (P = 9.3 × 10−5). Notably, the variant most strongly associated with BMI (rs1558902-A in FTO) did not associate with smoking behavior. The association with smoking behavior is not due to the effect of the SNPs on BMI. Our results strongly point to a common biological basis of the regulation of our appetite for tobacco and food, and thus the vulnerability to nicotine addiction and obesity.

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Keywords: addiction; body mass index; nicotine dependence; obesity; smoking

INTRODUCTION
Smoking and obesity are major risk factors for many serious diseases.1,2 Eating and smoking are behavioral traits that are at least in part controlled by the same reward mechanisms.3 Genome-wide association studies (GWAS) have yielded 32 single-nucleotide polymorphisms (SNPs) associated with body mass index (BMI).4 Smoking and SNPs associated with increased smoking quantity have been shown to correlate with lower BMI.5,6 According to the World Health Organization (WHO), more than one billion people smoke and over 400 million people are obese (BMI > 30 kg m−2), with both prevalences rising (see url section). Eating can become compulsive, and the neurobiological processes relating to overindulgence in food overlap with those involved in substance abuse and addiction.3 All drugs of abuse have been shown to increase dopamine in the mesolimbic reward system, and studies of both human brain images5 and animal brains6 have revealed that similar neural circuits are involved in the regulation of rewarding and reinforcement in drug addiction and compulsive eating. Based on the many similarities between hyperphagia and excessive drug use in addiction, it has even been suggested that some forms of obesity should be included as a diagnosis in future editions of the Diagnostic and Statistical Manual of Mental Disorders.8,9 Smoking influences body weight, such that smokers weigh less than non-smokers, and smoking cessation is often accompanied by an increase in weight.5 These effects have been largely attributed to nicotine that increases the metabolic rate and suppresses appetite. Although increased food intake upon smoking cessation is partly explained by a reward substitution mechanism, as food intake is increased to make up for the lack of nicotine, the absence of nicotine has also been shown to increase the reward value of certain foods.10 At the molecular level, these effects are most likely achieved through activation of the nicotinic acetylcholine receptors. The melanocortin (MC) system has a key role in regulating body weight,11 and nicotine was recently shown to interact directly with the MC system in the brain through activation of α3β4 nicotinic acetylcholine receptors on pro-opiomelanocortin (POMC) neurons12 in the arcuate nucleus of the hypothalamus. The POMC neurons project to secondary neurons influencing appetite, and nicotine activation leads to the release of melanocortin-4 agonists activating MC4 receptors in the paraventricular nucleus producing appetite suppression, an effect that is absent from POMC KO mice.12

However, the relationship between smoking phenotypes and obesity is more complicated than can be accounted for by the known effects of nicotine on appetite and metabolism. This is evident from the fact that the number of cigarettes smoked per day (CPD) correlates with elevated BMI.13,14 Thus, although smokers weigh less than non-smokers, heavy smokers indeed weigh more than light smokers. BMI and smoking data are widely available from various studies and large sample sizes have been obtained for GWAS of BMI and some smoking phenotypes,15–17 and these studies have uncovered a number of variants associating with obesity (BMI) and with smoking behavior. The variant most strongly correlating with CPD,16–17 rs1051730-A/rs16969968-A, correlates with reduced BMI both in current and former smokers, but does not have an impact on the BMI of never smokers.8 This observation is

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The collaborators from these consortia are listed in a section entitled CONSORTIA.

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consistent with the notion that smoking influences body weight through nicotine’s effects on body and brain, the increase of metabolic rate and suppression of appetite. Here we report how variants correlating with BMI influence smoking behavior.

MATERIALS AND METHODS

Study subjects

Written informed consent was obtained from all subjects. Inclusion in the study required the availability of genotypes from ongoing SNP array typing in Iceland or previous GWAS. The study populations have all been described previously. The GWAS of smoking initiation (SI) involved comparison of ever smokers and never smokers, and the studies of smoking quantity probed CPD as a quantitative trait among smokers only. The definitions of smokers and never smokers varied somewhat between studies, as questions addressing smoking behavior varied with most studies probing for regular smoking over a certain period of time. Questions probing for smoking quantity also varied between studies, and for analysis of smoking quantity we used CPD data for smokers in categories with each category representing 10 CPD (effect size of 0.1 = 1 CPD). CPD at the time of smoking was used for past smokers, and never smokers were excluded from analysis of CPD. All subjects were of European descent. The total sample sizes were N = 100,860 and N = 161,490 for CPD and SI, respectively.

Icelandic study design

A generalized form of linear regression was used to test the correlation between quantitative traits (BMI and height) and smoking phenotypes (CPD and SI) in Iceland. The generalized form assumes that the smoking behavior of related individuals is correlated proportional to the kinship between them rather than assuming that the smoking phenotypes of all individuals are independent. Let y be the vector of smoking behavior measurements, and let x be the vector of BMI or height measurements. We assume that the expectation of the smoking behavior depends linearly on BMI or height, \( E(y) = \beta x \), and that the variance–covariance matrix of the smoking behavior depends only on the pairwise kinship between the study participants, \( \text{Var}(y) = 2\sigma^2 k \), where

\[
\Phi_k = \frac{1}{2p} k_{ij} \neq j
\]

is based on the kinship between individuals as estimated from the Icelandic genealogical database (\( k_{ij} \)) and an estimate of the heritability of the trait (\( \sigma^2 \)). Assuming normally distributed errors, the maximum likelihood method gives estimates for \( \beta \) which will asymptotically follow a normal distribution and can be used to estimate the correlation between height and BMI on the one side and CPD and SI on the other.

In order to test the correlation between the set of 32 BMI SNPs or the set of 180 height SNPs and smoking behavior, the same type of analysis was performed as described previously. The GWAS of smoking initiation (SI) involved comparison of ever smokers and never smokers, and the studies of smoking quantity probed CPD as a quantitative trait among smokers only. The definitions of smokers and never smokers varied somewhat between studies, as questions addressing smoking behavior varied with most studies probing for regular smoking over a certain period of time. Questions probing for smoking quantity also varied between studies, and for analysis of smoking quantity we used CPD data for smokers in categories with each category representing 10 CPD (effect size of 0.1 = 1 CPD). CPD at the time of smoking was used for past smokers, and never smokers were excluded from analysis of CPD. All subjects were of European descent. The total sample sizes were N = 100,860 and N = 161,490 for CPD and SI, respectively.

RESULTS AND DISCUSSION

To study the correlation between obesity variants and smoking phenotypes, we focused on the 32 SNPs associating with BMI

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Association of BMI, height and SNPs associating with BMI and height with smoking phenotypes in Iceland</th>
</tr>
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<tbody>
<tr>
<td><strong>From</strong></td>
<td><strong>CPD</strong></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td><strong>Correlation (95% CI)</strong></td>
</tr>
<tr>
<td>BMI</td>
<td>33620</td>
</tr>
<tr>
<td>32 BMI SNPs</td>
<td>24618</td>
</tr>
<tr>
<td>Height</td>
<td>33875</td>
</tr>
<tr>
<td>180 Height SNPs</td>
<td>24630</td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; CI, confidence interval; SNP, single-nucleotide polymorphism.
described in a recent report of a study of 249,796 subjects. We weighted the 32 SNPs together based on their published effect on BMI and tested the correlation with both CPD and SI in 49,565 chip-typed Icelanders (Table 1). We also tested the correlation between the actual measured BMI and the smoking phenotypes in a slightly larger set of Icelanders. For comparison, we performed a corresponding study using Icelandic data on human height and 180 SNPs reported to influence human height in a recent study of 183,731 individuals (Table 1).

BMI associated with CPD ($r = 0.095, P = 2.5 \times 10^{-06}$) but not SI ($r = -0.005, P = 0.29$), whereas height did not associate with CPD ($r = -0.004, P = 0.46$) and showed only weak association with SI ($r = 0.012, P = 0.013$). The set of 32 BMI SNPs associated with both CPD ($r = 0.032, P = 8.0 \times 10^{-7}$) and SI ($r = 0.019, P = 0.00054$), whereas the set of 180 height SNPs associated with neither smoking behavior ($P = 0.84$ and 0.44 for CPD and SI, respectively).

The correlation between the set of 32 BMI SNPs and BMI and the correlation between BMI and CPD predict a correlation between the 32 BMI SNPs and CPD of 0.013, which is significantly lower than the observed correlation of 0.032 between the set of 32 BMI SNPs and CPD ($P = 0.0033$). The correlation between BMI and SI is negative so that the predicted correlation between the 32 BMI SNPs and SI is also negative and even more significantly different from the observed correlation of 0.019 than from 0. Hence, the observed associations between the BMI variants and the smoking phenotypes are not explained by the direct phenotypic correlations between BMI and smoking behavior.

To investigate the contributions of individual SNPs and to replicate our observations in other populations, we looked up the correlations of each of the 32 SNPs with CPD and SI, using data from our previous studies outside of Iceland ($N = 76,242$ for CPD, and $N = 127,274$ for SI). For these studies, we utilized the fixed-effect additive meta-analysis results for ~2.5 million SNPs obtained using the inverse-variance method for each of the two smoking phenotypes. Before conducting the meta-analysis, we performed a genomic control correction of each study. The combined $\chi^2$-test statistics were still somewhat inflated by a factor of $\lambda_{GC} = 1.10$ (SI) and $\lambda_{GC} = 1.06$ (CPD). The correlations between the set of 32 BMI SNPs and the two smoking variables were significant in this replication sample with $P = 1.2 \times 10^{-5}$ and $9.3 \times 10^{-5}$ for SI and CPD, respectively. Combined with Iceland, the association between the 32 BMI SNPs and SI and CPD reached a significance of $P = 1.2 \times 10^{-7}$ and $P = 1.6 \times 10^{-9}$, respectively.

As expected, based on the correlations observed between the combined set of the 32 BMI SNPs (Table 1), we observe congruence in the effects that these SNPs have on BMI and smoking behavior. For most of the SNPs, the allele that associates with increased BMI also associates with both increased probability of SI and higher CPD (Figure 1). We note that the effect sizes are small and although the markers as a group clearly associate with smoking behavior. A variant within the BDNF gene cluster (rs286125-C) is among the top markers ($P < 0.05$) for both SI (effect = 0.186, $P = 0.0244$) and CPD (effect = 0.0097, $P = 0.0305$). A SNP within the BDNF gene has previously been shown to associate with smoking initiation (rs6265-C). This SNP is in linkage disequilibrium with the BMI-associated rs10767664 ($r^2 = 0.85$ in Iceland). The association with SI remains significant after removing rs10767664 ($P = 1.3 \times 10^{-5}$).

In summary, we have demonstrated that as a group, the 32 common variants identified in GWAS of BMI also have an impact on the smoking behavior. A variant within the nAChR gene cluster
at chr 15q25 (rs1051730-A) was discovered in GWAS of smoking behavior,20,21 and subsequently shown to correlate with reduced BMI in smokers without an effect on the BMI of never smokers,6 thus most likely influencing BMI mainly through its effect on smoking behavior. The variants studied here represent a different class of SNPs affecting both BMI and smoking: They were found in GWAS of BMI and influence BMI in both smokers and never smokers, and the alleles correlating with elevated BMI tend to increase the propensity to smoke and/or associate with increased cigarette intake. We note that, in Iceland, the correlation between the predicted BMI and observed BMI is similar for smokers (0.15, \( P = 3.0 \times 10^{-3}\), \( N = 20,462\)) and never smokers (0.13, \( P = 7.2 \times 10^{-33}\), \( N = 7910\)). The direction of this trend is opposite to what would be expected based on the known effects of nicotine on BMI, and inconsistent with an effect rooted in nicotine-mediated increase of metabolic rate and suppression of appetite. That the majority of variants known to associate with elevation of BMI correlate with smoking behaviors in this manner points to a common biological basis to regulation of the intake of food and tobacco.

CONFLICT OF INTEREST

Authors whose affiliations are listed as Decode genetics/AMGEN are employees of Decode genetics/AMGEN.

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AUTHOR CONTRIBUTIONS

TET, DFG, and KS wrote the manuscript. The study was designed by and the results interpreted by TET, DFG, PS, SB, UT and KS. The meta-analyses of smoking GWAS data were performed by DFG. TET, DFG, PS, SB, US, GT, BW and VS worked on data management and analysis. Smoking GWAS consortia were coordinated by HF (TAG), PFS (TAG) JM (OX-GSK) and MIM (ENGAGE). All authors contributed to the final version of the paper.

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Supplementary Information accompanies the paper on the Translational Psychiatry website (http://www.nature.com/tp)

CONSORTIA

The data utilized came from three large GWAS done by the ENGAGE, TAG, and OX-GSK consortia (references 15–17). The additional collaborators from these three consortia are listed below.


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Common biological basis of obesity and nicotine addiction

TE Thorgeirsson et al

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Translational Psychiatry (2013), 1 – 7
Common biological basis of obesity and nicotine addiction

TE Thorgeirsson et al

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Heinrich28,29,30, Rajesh Rawal28, Norbert Dahmen31, Claudia Lambina32,33, Ozren Polasek34, Lina Zgaga34, Jennifer Huffman35, Susan Campbell35, Jaspal Kooner36, John C Chambers13,14, Mary Susan Burnett36, Joe Devaney36, Augusto D Pichard36, Kenneth M Kent36, Lowell Satler36, Joseph M Lindsay36, Ron Waksman37, Stephen Epstein38, Jim F Wilson39, Sarah H Wild39, Harry Campbell39, Veronique Vitart40, Muredach P Reilly40,41, Mingyao Li41, Li Ming42, Roberto Willemsen42, William Matthai43, Hakon H Hakonarson43, Daniel J Rader44, André Franke44, Michal Wiegand45, Arne Schäffer46, Manuela Uda45, Antonio Terracciano46, Xiangjun Xiao42, Robert Wilensky40, William Matthai43, David Slagsvold44, David St Clair45, Dan Rujescu46, Gonçalo R Abecasis47, Hans Jörgen Grabe47, Alexander Teumer48, Henry Völzke53, Astrid Petersmann54, Ulrich John55, Igor Rudan56, Caroline Hayward56, Alan F Wright57, Ivana Kolic58, Benjamin J Wright58, John R Thompson56,59, Anthony J Balmforth60,61, Martin Farrall62, Anna 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Common biological basis of obesity and nicotine addiction
TE Thorgeirsson et al

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Translational Psychiatry (2013), 1 – 7