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Menthol smokers: metabolomic profiling and smoking behavior

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Abstract

Background—The use of menthol in cigarettes and marketing is under consideration for regulation by the FDA. However, the effects of menthol on smoking behavior and carcinogen exposure have been inconclusive. We previously reported metabolomic profiling for cigarette smokers, and novelly identified a menthol-glucuronide (MG) as the most significant metabolite directly related to smoking. Here, MG is studied in relation to smoking behavior and metabolomic profiles.

Methods—A cross-sectional study of 105 smokers who smoked two cigarettes in the laboratory one hour apart. Blood nicotine, MG and exhaled carbon monoxide (CO) boosts were determined (the difference before and after smoking). Spearman's correlation, Chi-Square and ANCOVA adjusted for gender, race and cotinine levels for menthol smokers assessed the relationship of MG boost, smoking behavior, and metabolic profiles. Multivariate metabolite characterization using supervised Partial Least Squares-Discriminant Analysis (PLS-DA) was carried out for the classification of metabolomics profiles.

Results—MG boost was positively correlated with CO boost, nicotine boost, average puff volume, puff duration, and total smoke exposure. Classification using PLS-DA, MG was the top metabolite discriminating menthol vs. non-menthol smokers. Among menthol smokers, forty-two metabolites were significantly correlated with MG boost, which linked to cellular functions such as of cell death, survival, and movement.

Conclusion—Plasma MG boost is a new smoking behavior biomarker that may provides novel information over self-reported use of menthol cigarettes by integrating different smoking measures for understanding smoking behavior and harm of menthol cigarettes.

Impacts—These results provide insight into the biological effect of menthol smoking.

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Keywords

Menthol; Metabolomics; Plasma; Tobacco Smoke; UPLC-QTOF-MS

Introduction

In 2009, the Food and Drug Administration (FDA) was mandated by the Family Smoking Prevention and Tobacco Control Act to regulate tobacco products and ban flavor additives. However, the act exempted menthol from the ban pending FDA review and consideration of the available science. In March 2011, the Tobacco Product Scientific Advisory Committee (TPSAC) has found adverse impact on public health by increasing the numbers of smokers with resulting premature death and avoidable morbidity, and recommended that “removal of menthol cigarettes from the marketplace would benefit the public health (1). The FDA’s Center for Tobacco Products separately has done extensive literature reviews on topics regarding menthol and tobacco, and concluded that the studies that examined menthol cigarette usage associated with smoking topography are inconsistent and limited (2). From its preliminary scientific evaluation (3), menthol in cigarettes also was considered by the FDA to likely have significant public health impacts. On July 2013, the FDA further issued an Advance Notice of Proposed Rulemaking (4) seeking additional information from science-based approaches to further inform decisions about regulatory action with respect to menthol in cigarettes.

Menthol cigarettes are highly popular among African-American smokers, although many Caucasians also smoke them (5). Used as a flavoring that provides a cooling sensory effect that reduces the harshness and irritation inherent in cigarette smoke, almost all cigarettes contain some degree of menthol (6). Menthol-labeled cigarettes are marketed with messaging such as “fresh”, “clean”, and “refreshing” by the tobacco industry, and attract specific demographic groups including adolescents and young adults, women, and African Americans (7–10). From a recent meta-analysis, when compared to never smokers, current menthol cigarette smokers have a statistically significant hazard ratio of 3.48 for cardiovascular mortality, while the ratio was 2.10 for current non-menthol smokers (11).

Menthol cigarette usage is associated with greater addictive potential, increased initiation and dependence, and longer time to achieve cessation (3). Duner-Engstrom *et al* reported that menthol increased salivary secretion that could facilitate the absorption of nicotine in the mouth (12). Other studies have found its effect to prolong breath-hold time (13), and to increase the permeability of N-nitrosornicotine (NNN) and nicotine (14). Moreover, menthol smokers showed impaired nicotine metabolism (15), have a lower detoxification rate of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL) (16), and retained more ultrafine particulate and fine particulate benzo(a)pyrene than non-menthol smokers (17). As a result, menthol cigarette smokers may take in more carcinogens. Because of its sensory property and respiratory effects, menthol has been hypothesized to affect smoking topography (e.g., how someone smokes their cigarettes) by increasing the puff volumes, leading to smokers’ exposure to more hazardous chemicals (18). For cancer outcomes, Sidney *et al.* (19) reported a modestly increased risk of lung cancer associated with male

menthol smokers (relative risk = 1.45, 95% CI 1.03–2.02). Other studies also had shown an increased risk of menthol smoking with lung cancer (20), pharyngeal cancer (21), and esophageal cancer (22) among menthol smokers, although the results were not always statistically significant.

Recently, an untargeted metabolomics approach by Ultra-Performance Liquid Chromatography-Quadrupole-Time of Flight Mass Spectrometry (UPLC-Q-TOF MS) was used with a pre-post experimental design where dynamic changes of plasma metabolites could be examined in a cross-sectional study of smokers (n=105) who smoked 2 cigarettes one hour apart, we reported that thirty-one novel metabolites were affected by cigarette smoking during this interval, uniquely including MG (23). Here, the study extend our investigation by examining the associations of MG changes during smoking, termed the MG boost, as well as other smoke exposure biomarkers, smokers' puff profiles, the classification of metabolomic profiles between menthol and non-menthol smokers, and the biological associations of MG in menthol smokers' plasma with their metabolome. Using an untargeted metabolomics approach, this study hypothesized that the MG boost would identify metabolic pathways that are changed by menthol exposure.

Materials and Methods

Study recruitment and design

A previously conducted cross-sectional study with a pre-post smoking experimental design was used to determine smoking behavior and novel blood biomarkers before and after smoking cigarettes (23). Subjects 18 years of age and who smoked >10 cigarettes/day for at least 5 years with a stable smoking pattern for 1 year were recruited through local media. Eligible subjects were excluded from the study if they had a prevalent respiratory or oral cavity disease, prior history of cancer, or had undergone general anesthesia within six months. Subjects who had used medications for smoking cessation (including nicotine replacement therapy) or antidepressants within six months, or used other tobacco products in the past year were further excluded. All subjects gave informed consent and the study protocols were approved by the Institutional Review Boards at the respective institutions.

Smoking Protocol and Biospecimen Collection

All participants were asked to smoke two cigarettes of their usual brand in a smoking laboratory, one hour apart. Participants were first asked to smoke one of their own cigarettes as naturally as possible, and to smoke their second cigarette through the mouthpiece to assess smoking topography (CReSS; Borgwaldt KC, Richmond, VA) via a transducer to measure puff volume, puff duration, inter-puff interval, number of puffs, time to smoke the cigarette, and puff velocity. From these data, total smoke exposure (puff number × puff volume) was calculated. Carbon monoxide (CO) levels in the participants' expired air were determined immediately before and after each of the two cigarettes (Vitalograph Inc, Lenexa, KS). Blood was collected immediately before and two minutes after smoking each cigarette. This allowed for the assessment of the change of biomarker levels (nicotine and MG) due to smoking a cigarette (i.e., the "boost" measurement). Nicotine, cotinine and trans-3'-hydroxycotinine levels in the blood samples were determined by gas

chromatography (nicotine) or liquid chromatography–tandem mass spectrometry (cotinine and trans-3'-hydroxycotinine) in the laboratory of Dr. Neil Benowitz, as previously described (24, 25). The nicotine metabolic ratio (NMR) was calculated using the ratio of plasma 3'-hydroxycotinine to cotinine, as a measure of nicotine metabolic capacity. Six subjects with negative nicotine boost levels and seven subjects with plasma cotinine levels less than 100 ng/ml were excluded to ensure that subjects had an active smoking history in the study. These six smokers with negative boosts likely smoked their cigarette differently, and minimally, compared to their usual smoking behavior. It is possible that the subjects with negative boost levels had minimal puff and inhalation during the boost assessment (in contrast to their normal smoking pattern), and so it is appropriate to exclude them. A total of 105 subjects were left for the analysis.

A questionnaire was administered in person by trained interviewers during the 60 minutes between cigarettes. Data was collected on demographic characteristics, smoking history, and other lifestyle factors (including alcohol use, and body size) and personality traits related to smoking behavior. Subjects were also administered the Fagerstrom Test for Nicotine Dependence (FTND).

Significant Metabolites from Untargeted Metabolomics Analysis

420 plasma samples from 105 smokers (4 samples each) and 117 quality control samples and repeats were analyzed by UHPLC-Q-TOF MS for the untargeted metabolomics profiles, using both a positive and negative ion mode (total of 1,074 assays) on an ACQUITY UPLC system (Waters, Milford, MA) and processed by XCMS online (XCMS Public Shares Job ID: 1110757 & 1110926) (26). From the previous result, novel metabolites consistently and similarly affected across two cigarettes were identified and eleven metabolites were validated by matching the retention time, mass error and isotopic pattern and tandem mass spectrum of the parent ion from the biological sample to that of the commercially available standard metabolites and were included in this study.

Data Analysis

All data was analyzed using SIMCA (Umetrics Inc, Kinnelon, NJ) and Partek Genomics Suite (Partek Inc, St Louis, MO). *T*-tests and chi-square (X^2) tests were performed to evaluate differences in smokers' characteristics between menthol and non-menthol smokers. Spearman's rank correlation was performed to assess correlations for smoking-related variables and metabolites. A partial Least-Squares Discriminant Analysis (PLS-DA) model was constructed for multivariate metabolite characterization. ANCOVA models adjusted for gender, race and cotinine levels were carried out to determine the relationship of MG boost from the second cigarette among menthol smokers to their metabolomics profiles. Significant metabolites were searched against METLIN Metabolomics Database, Human Metabolome Database (HMDB), and LIPID MAPS Structure Database (LMSD) with the mass accuracy of ten parts per million to identify putative metabolite identifications. The construction, interaction, and pathway analysis of potential biomarkers was performed by Ingenuity Pathways Analysis (IPA).

Results

Characteristics of the 105 study participants (mentholated cigarette smokers, $n=71$ versus non-mentholated, $n=34$) are shown in Table 1. The mean age \pm standard deviation of participants was 43.1 ± 9.6 years old, with an average smoking history of 22.9 ± 9.9 years. The mean cotinine level of smokers was 252.6 ± 103.3 ng/ml, and the mean NMR was 0.38 ± 0.22 . Approximately 64% were male and the mean FTND score was 5.0 ± 2.3 . Aside from race, where menthol smokers were predominantly African-American ($P<0.00001$), no significant differences in participant characteristics were observed by type of cigarette smoked.

In order to examine the correlation of the eleven smoking-related metabolites to variables related to smoking behavior, Spearman's rank correlation coefficient was computed on the metabolite boosts (i.e., the level changed) from the 2nd cigarette to the smoking-related variables (Supplemental table 1). Since blood cotinine level is a biochemical measure of nicotine consumption, rather than self-reported use (27), plasma cotinine levels were used in the analysis to represent smokers' cigarette exposure. From the results in Supplemental table 1, the MG boost had the most statistically significant correlations among all validated metabolites with smoking-related variables; it was positively correlated with the average puff volume ($r=0.36$; $p=0.0003$), CO boost ($r=0.31$; $p=0.001$), average puff duration ($r=0.3$; $p=0.003$), total smoke exposure ($r=0.26$; $p=0.01$), and nicotine boost ($r=0.26$; $p=0.04$) (Supplemental table 1 and Supplemental figure 1). There was no correlation of the MG to cigarettes per day or time to first cigarette, probably due to the quick half-life of the MG. When adjusted with cotinine levels in the model (Supplemental table 2), average puff volume, CO boost, number of puffs, 3-hydroxy cotinine, and NMR were significantly correlated with MG boost. However, no significant correlations were found between MG boost and average inter-puff interval, maximum puff velocity, and FTND.

When smokers were stratified by menthol and non-menthol status, the MG boost from menthol smokers was positively correlated with average puff volume ($r=0.48$; $p=6.22E-05$), average puff duration ($r=0.33$; $p=0.008$), total smoke exposure ($r=0.35$; $p=0.004$), and negatively correlated with inter-puff interval ($r=-0.37$; $p=0.002$) (Table 2). On the other hand, the MG boost from non-menthol smokers was positively correlated only with CO boost ($r=0.47$ $p=0.006$), and not significantly correlated with other variables. An increased correlation of MG boost versus FTND in menthol smokers ($r=0.22$; $p=0.06$) compared to non-menthol smokers ($r=0.02$; $p=0.9$) was found, and an increased correlation of MG boost versus nicotine boost in menthol smokers ($r=0.32$; $p=0.05$) compared to non-menthol smokers ($r=0.28$; $p=0.19$) was observed. Significant correlations were also found between pre- and post-cigarette MG levels to the topography profiles (Supplemental table 3).

Spearman's rank correlation was further computed on the 2nd nicotine boost and 2nd CO boost to smoking-related variables, separately. From the results, nicotine boost was negatively correlated with NMR in all smokers ($r=-0.27$; $p=0.03$), positively correlated with MG boost in all smokers ($r=0.26$; $p=0.04$), and positively correlated with FTND in menthol smokers ($r=0.38$; $p=0.02$, Supplemental table 4). On the other hand, CO boost was positively correlated with MG boost in all smokers ($r=0.31$; $p=0.001$) and non-menthol smokers

($r=0.47$; $p=0.006$), and positively correlated with average puff volume in non-menthol smokers ($r=0.38$; $p=0.04$, Supplemental table 5).

Two sample t tests were computed to assess the differences in smoking-related characteristics between self-reported menthol and non-menthol smokers (Table 3). Menthol smokers had significantly higher MG boosts, compared with smokers of non-menthol cigarettes that still contain small amounts of menthol ($p<0.00002$, fold change = 11.2). The range for the MG boost in menthol smokers was -41.3 to 259.6 (Supplemental figure 1, red dots), with a mean of 31.2 and a median of 22.7 , while in non-menthol smokers the range was -44.7 to 67.5 , with a mean of -2.8 and a median of -3.7 (Supplemental figure 1, blue dots), respectively. However, there were no significant differences in the FTND scores, CO boost, nicotine boost, NMR, and any topography profiles between menthol versus non-menthol smokers, including maximum puff velocity, average puff volume, average puff duration, average inter-puff interval, total number of puffs, and total smoke exposure (Table 3). Specificity analysis using median MG boost values to categorize smokers with high and low plasma MG boost presents a sensitivity of 70% in identifying menthol smokers with a positive predictive value of 94.2%, and 91% in the specificity to identify non-menthol smokers.

Metabolomics profiles of menthol and non-menthol smokers using PLS-DA were well-separated with a CV-ANOVA P value of 0.0003 (Figure 1a) using type of cigarettes as the classifier, and MG displayed the strongest discriminatory power among all metabolites in the model (Figure 1b) with a Variable Importance in Projection (VIP) score > 2.5 . In order to examine the biological impact of MG boost from the second cigarette to smokers' metabolomics profiles, a subset analysis was conducted using an ANCOVA model adjusted for gender, race and cotinine levels of 71 menthol smokers in relation to the metabolomics profiles after second cigarette. There were 653 metabolites significantly correlated with MG boost ($p < 0.05$), and 42 of them were significant after correction for multiple comparisons ($q < 0.05$). The main chemical taxonomy classes of the 42 metabolites were putatively identified as glycerophospholipids ($n=5$), carboxylic acids and derivatives ($n=4$), sterol lipids ($n=2$), prenol lipids ($n=2$), alkaloids and derivatives ($n=1$), benzene and substituted derivatives ($n=1$), fatty acyls ($n=1$), indoles and derivatives ($n=1$), organic sulfuric acids and derivatives ($n=1$), alkaloids and derivatives ($n=1$), and terpenoids ($n=1$) (Table 4). Among the correlated metabolites, menthol-glucuronide, 2,4-dihydroxyacetophenone 5-sulfate, *L*-tryptophan, uric acid, benzyl sulfate, bilirubin, oxalosuccinic acid, PC(O-16:0/22:6), PC(22:2/16:1) were positively correlated with MG boost, and S-(PGA2)-glutathione, PC(O-12:0/O-1:0), thalicoside A, PE(P-16:0/0:0), 2-(1-ethoxyethoxy)propanoic acid, 2-deoxy-20-hydroxyecdysone 22-phosphate, N-ornithyl-L-aurine, 10-oxo-nonadecanoic acid, 20-hydroxyecdysone, isothankunic acid, and lysoPC(20:4) were negatively correlated with MG boost (Table 4). Twenty-two metabolites could not be mapped to current databases and their identities remain unknown.

Pathway analysis was conducted using available KEGG IDs from their putative metabolites and projected onto Ingenuity's knowledge-based networks. Considered in this analysis were direct and indirect relationships, including endogenous chemicals, focusing on interaction networks observed from all data sources. There were four KEGG IDs mapped by IPA for the

analysis, namely *L*-tryptophan, uric acid, bilirubin, and *L*-acylglycerophosphocholine (representing 5 glycerophospholipids in the study). Network analysis was generated *de novo* based on the mapped metabolites to explore potential molecular events and mechanisms affected by MG boost. The network affected by the MG boost (Figure 2) was associated with functions of cell death and survival, cellular movement, hematological system development and function, with 7 molecules involved in cancer, namely ABCB4, C3, CASR, CCK, IDO1, *L*-tryptophan, and UMOD (Figure 2).

The ANCOVA model adjusted for gender, race and cotinine levels was performed to model the association between MG boost and the metabolomics profiles of 34 non-menthol smokers, as well as correlation between CO boost/and nicotine boost for menthol and non-menthol smokers, separately (data not shown). However, none of results reached statistical significance after correction for multiple comparisons.

Discussion

Menthol marketed cigarettes represent more than a quarter of all cigarettes sold in the United States (28). They are known as a starter product fostering initiation in youth (9), and menthol smokers are known to have greater nicotine dependence (10) and are less successful in quit attempts (29). The use of menthol in tobacco products is currently not regulated, but the FDA is considering the removal or regulation of menthol in tobacco and restricting its marketing (30). From our previous study using a pre-post experimental design where an individual smoked two cigarettes to assess biomarker changes with smoking, allowing for within-subject replication, MG was the most significant metabolite that rose after each cigarette smoking ($p=6.99E-10$, $q=8.90E-07$) independent of gender, race, and plasma cotinine levels, and baseline MG level was positively correlated with cotinine levels in all smokers ($p=0.04$) and menthol smokers ($p=0.008$) (23). In this study, the associations of the MG boost from the second cigarette were examined, after a 1hr standardized time interval, to various smoking-related variables including topography profiles. The result showed that MG boost was positively associated with CO boost, nicotine boost, average puff volume, average puff duration, and total smoke exposure. Although the correlation was more significant among menthol smokers than non-menthol smokers, some of the non-menthol smokers did exhibit higher MG boost than menthol smokers (Supplemental figure 1), revealing the disadvantage of using the traditional dichotomous descriptors (menthol or non-menthol) in the evaluation of the actual menthol delivered from cigarette smoking. The sensitivity of MG boost showed that there is a 30% probability for a menthol smoker to have low MG boost in the plasma. Here, we evaluate the impact of menthol on smoking behavior using MG level delivered in plasma rather than self-reported cigarette usage in order for a more accurate estimation. The correlation was also significant between the direct observation of pre- and post-cigarette MG levels versus the topography profiles. This indicates the potential for the specificity without using a boost level. Thus, MG and MG boost is a marker of smoke exposure that reflects different types of exposure measurements and may provide better specificity for exposure and harm than self-reported menthol cigarette use or the other measures of exposure.

Generally, high correlation between topographical measures is expected (31). However, these measures are not interchangeable and can be affected by gender, smoking dependence, and cigarette smoked per day (32–34). Therefore, all parameters need to be recorded and evaluated separately when measuring smoking topography (32). Studies on the topography measures also indicated that they are not kept constant during the course of smoking a cigarette, where puff volume decreases and inter-puff interval initially increases and then decreases (31). To date, it has been unclear if menthol cigarette use affects exposure through topography, because prior studies are contradictory regarding its effects on puff volume (35–42), number of puffs (36–39, 41, 43, 44), and other topography measures (36, 38, 45). Conclusions from these studies are limited due to differences in study design, small sample sizes, differences in the nicotine and tar yield, and differences in the menthol content of the cigarettes used (2). Importantly, no studies to date assessed topography in terms of actual menthol exposure, but only self-reported use of menthol cigarettes. In contrast, in this study, the change in the MG boosts for menthol smokers was related to smoking topography.

The MG boost was positively correlated to the CO and nicotine boosts. Prior studies have not been conclusive regarding differences in nicotine and CO boosts between menthol and non-menthol smokers, ranging from increased and decreased correlations to no effect (36–39, 43, 44, 46–49). From our results, no significant differences in nicotine boost and CO boost were observed between menthol and non-menthol smokers. Correlations of nicotine boost and CO boost to the smoking-related variables were also examined, but almost none of the smoking-related variables were correlated with either nicotine or CO boost (Supplemental table 4 and 5). Furthermore, from the ANCOVA model adjusted for gender, race and cotinine levels performed to model the association between CO boost and the metabolomics profiles, none of the metabolites from analyses reached significance. Thus, the MG boost provides better relationships to topography and inhalation, compared to nicotine and CO boost measurements.

Menthol is highly volatile and has a high diffusion rate into smoke (50). It is added in many synthetic forms to tobacco in ways to deliver the compound in smoke more efficiently without fluctuations in the yields (51). Mentholated cigarettes are perishable products and thus the levels of menthol can vary by the storage time, temperature (18), brand, product (6), and by shelf-life (52). All cigarettes contain menthol to some extent (6), but the menthol-labeled cigarettes have about 1.5–2 fold more menthol than non-menthol cigarettes (6). Gelal *et al.* has reported plasma levels of the MG in non-smokers who were administered menthol capsules, candies and mint tea, where the metabolites have the same characteristics of the MG that we identified, and providing further evidence that we are studying the MG as a metabolite of menthol (53). However, the method requires *in vitro* treatment of the plasma samples with β -glucuronidase enzyme. Benowitz *et al.* has reported urine levels of the MG as biomarker of exposure in menthol smokers with an improved method by liquid chromatography–mass spectrometry (54). Other study have reported the assessment of MG in humans related menthol in the treatment of gastrointestinal disease using gas chromatography–mass spectrometry in urine and plasma (53, 55, 56). In this study, by using a robust method UPLC-Q-TOF MS which allows better separation and resolution for the untargeted metabolomics, MG was detected simultaneously with smokers' metabolomics profiles. This provides new opportunities for human studies of menthol tobacco products.

For example, e-cigarette vapors do not have most of the tobacco toxicants, but some are mentholated and so the menthol-glucuronide might be useful for studies of e-cigarettes that need to assess exposure. The MG boost range was substantially more in the menthol smokers than the non-menthol smokers, which is both consistent with how levels vary among these cigarettes, but also that menthol smokers are inhaling and absorbing substantially more menthol.

Some previous studies have investigated the effect of cigarette smoking on metabolomics profiles, but none have reported the presence of the MG boost. Müller *et al.* investigated the differences in the fatty acid and phospholipid species among plasma of smokers and non-smokers by GC-TOF-MS (57), and found elevated levels of PC and PE species in smokers containing monounsaturated fatty acids in smokers. KORA (Cooperative Health Research in the Region of Augsburg) study performed a targeted metabolite profiling of 198 metabolites on 283 human sera samples. They observed 3 long-chain acyl-alkyl-phosphatidylcholines decreased in current smokers comparing to former, and non-smokers in their first report (58), and later in the follow-up study found decreased in glycerophospholipid pathways (59). In the study reported herein, forty-two metabolites were significantly correlated with MG boost ($q < 0.05$), which mapped to networks associated with functions of cell death and survival, cellular movement, hematological system development and function (Figure. 2). Menthol has been shown to inhibit cell proliferation and to induce cell death (60, 61). The major network affected involved 7 known molecules for cancer and its biological functions, and two P450 enzymes (CYP3A4 and CYP2B6, Figure 2). Menthol was reported to be an inhibitor of CYP3A4 (62) and CYP2B6 (63), and both were associated with altering the nicotine CYP2A6 metabolism (64). Nicotine metabolism is impaired among menthol smokers (15), and detoxification of the potent lung carcinogen NNAL was found lower in menthol smokers (16). The MG boost was positively correlated with NMR when controlling for cotinine (Supplemental table 2). Furthermore, MG level in urine was highly correlated with nicotine metabolites, NNAL, and polycyclic aromatic hydrocarbon (PAH) metabolites (54). Our results revealed the metabolic association of menthol on nicotine metabolism. Further studies should be conducted taking variables associated with individual's nicotine metabolic ratio into account in order to elucidate the impacts of menthol on the nicotine metabolism.

Among the metabolites that were correlated with the MG boost, glycerophospholipids were the most abundant compound class (Table 4). Glycerophospholipids are amphipathic lipids serve as important constituents of cell membranes that help to maintain structural integrity and ion permeability, as well as pulmonary surfactant to reduce surface tension during expiration (38). LysoPCs, specifically, are biologically potent compounds presenting as minor phospholipids in the plasma (8–12%) and cellular membranes (3%) (65). They are involved in inflammatory reactions (66), in the regulation of neurotransmitters (67), and as signaling molecules which transmit signals for biological responses including cell differentiation (68), immune response (69), inflammation (70), oxidative stress (70), cell migration (71), mitogenesis (72), and apoptosis (72). Patients with atherosclerotic diseases (73) and sepsis (74) were found to have lower levels of plasma lysoPCs. LysoPCs are metabolites transiently generated by phospholipase A2 (PLA2) during the remodeling of glycerophospholipids (75, 76), and can be further hydrolyzed to glycerophosphocholine by

lysophospholipase (77). From our pathway analysis, phospholipase A2 (PLA2) was involved in the major network affected (Figure 2). It was reported that PLA2 modulated the activity of menthol receptor TRPM8 and lysophospholipids altered the sensitivity of TRPM8 (78, 79). Up-regulation of lysophospholipase and decreased levels of lysoPCs have been shown upon cigarette smoke exposure in mouse model (80) and among current smokers (59), and combined activities of secreted PLA2s and eosinophil lysophospholipases were also found to cause pulmonary surfactant dysfunction (77). Consistent with our metabolomics profiling, the results from transcriptomics data of smokers in our group also showed that PLA2G15 which codes for lysophospholipase III for the hydrolysis of glycerophospholipids was among the genes found significantly up-regulated on lymphocytes of smokers treated with cigarette smoke condensate (81). Thus, circulating glycerophospholipids could play an important role in the composition and metabolism of lung surfactants, for the determination of lung dysfunction, and can be a potential biomarker for early detection of lung cancer.

There are several strengths to this study. First, the pre-post study design that assessed smokers immediately before and after smoking a cigarette allowed for an untargeted assessment of metabolite boosts. This uniquely allowed for the examination of dynamic changes on the plasma metabolome regulated by the acute effects of cigarette smoking without confounding by other exogenous exposures that would affect the metabolome (e.g., diet, medication, and lifestyle). Using subset analysis for changes in the metabolomics profiles, metabolites affected by menthol were identified among menthol smokers which may reflect the biological impacts of menthol inhalation in blood. There are some limitations of this study, such as small sample size, limited statistical power for subset analyses, and causal relationships that cannot be established due to the cross-sectional nature of the study. Another limitation is that only one type of UPLC column and separation method was used, and although chosen to obtain the most comprehensive profile for our samples, would not identify highly polar metabolites, such as sugars and amino acids, and some smoke carcinogen metabolites. The identification of unknown metabolites is a major bottleneck in the metabolomics field. It is a complex and costly process limited by the number of commercially available standards, with intensive effort required, and often results in a low yield of correctly characterized metabolites. Therefore, identification of the unknown metabolites was not carried out in the present manuscript. However, spectral interpretation and structural elucidation of the unknown features are needed in the future in order to identify and validate the unknown features in the study.

In summary, a metabolomics assessment was applied to a pre-post experimental design in smokers to evaluate the acute effects of cigarette smoking. The identification of the plasma MG boost, which has not been previously reported, allows improvements in evaluating impacts of menthol smoke exposure and smoking behavior. This in turn may provide specificity for the assessment of exposures and harm in menthol smokers, integrating several smoking exposure parameters. The pathways identified herein may yield insights into biological effects of plasma menthol and tobacco-related pathogenesis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Committee TPSA. Administration CfTPotFaD. Menthol Cigarettes and Public Health: Review of the Scientific Evidence and Recommendations. 2011. p. 249
2. Lawrence D, Cadman B, Hoffman AC. Sensory properties of menthol and smoking topography. *Tob Induc Dis*. 2011; 9(Suppl 1):S3. [PubMed: 21624149]
3. Administration FaD. Administration FaD. Preliminary scientific evaluation of the possible public health effects of menthol versus nonmenthol cigarettes. Silver Spring, MD: 2013. p. 153
4. Administration FaD. Administration FaD. FDA invites public input on menthol in cigarettes. Silver Spring, MD: 2013.
5. Gardiner PS. The African Americanization of menthol cigarette use in the United States. *NicotineTobRes*. 2004; 6(Suppl 1):S55–S65.
6. Celebucki CC, Wayne GF, Connolly GN, Pankow JF, Chang EI. Characterization of measured menthol in 48 U.S. cigarette sub-brands. *Nicotine Tob Res*. 2005; 7:523–31. [PubMed: 16085523]
7. Kreslake JM, Wayne GF, Alpert HR, Koh HK, Connolly GN. Tobacco industry control of menthol in cigarettes and targeting of adolescents and young adults. *Am J Public Health*. 2008; 98:1685–92. [PubMed: 18633084]
8. Anderson SJ. Marketing of menthol cigarettes and consumer perceptions: a review of tobacco industry documents. *Tobacco control*. 2011; 20(Suppl 2):ii20–8. [PubMed: 21504928]
9. Klausner K. Menthol cigarettes and smoking initiation: a tobacco industry perspective. *Tobacco control*. 2011; 20(Suppl 2):ii12–9. [PubMed: 21504927]
10. Yerger VB. Menthol's potential effects on nicotine dependence: a tobacco industry perspective. *Tobacco control*. 2011; 20(Suppl 2):ii29–36. [PubMed: 21504929]
11. Jones MR, Tellez-Plaza M, Navas-Acien A. Smoking, menthol cigarettes and all-cause, cancer and cardiovascular mortality: evidence from the National Health and Nutrition Examination Survey (NHANES) and a meta-analysis. *PLoS one*. 2013; 8:e77941. [PubMed: 24205038]
12. Duner-Engstrom M, Larsson O, Lundberg J, Fredholm BB. Effect of nicotine chewing gum on salivary secretion. *Swed Dent J*. 1986; 10:93–6. [PubMed: 3460195]
13. Sloan ADC, SC, Eccles R. Prolongation of breath-hold time following treatment with an L-menthol lozenge in healthy man. *Journal of Physiology*. 1993; 473:53P.
14. Squier CA, Mantz MJ, Wertz PW. Effect of menthol on the penetration of tobacco carcinogens and nicotine across porcine oral mucosa ex vivo. *Nicotine Tob Res*. 2010; 12:763–7. [PubMed: 20511349]
15. Benowitz NL, Herrera B, Jacob P 3rd. Mentholated cigarette smoking inhibits nicotine metabolism. *J Pharmacol Exp Ther*. 2004; 310:1208–15. [PubMed: 15084646]
16. Muscat JE, Chen G, Knipe A, Stellman SD, Lazarus P, Richie JP Jr. Effects of menthol on tobacco smoke exposure, nicotine dependence, and NNAL glucuronidation. *Cancer Epidemiol Biomarkers Prev*. 2009; 18:35–41. [PubMed: 19124478]

17. Brinkman MC, Chuang JC, Gordon SM, Kim H, Kroeger RR, Polzin GM, et al. Exposure to and deposition of fine and ultrafine particles in smokers of menthol and nonmenthol cigarettes. *Inhal Toxicol.* 2012; 24:255–69. [PubMed: 22486344]
18. Yerger VB, McCandless PM. Menthol sensory qualities and smoking topography: a review of tobacco industry documents. *Tob Control.* 2011; 20(Suppl 2):ii37–43. [PubMed: 21504930]
19. Sidney S, Tekawa IS, Friedman GD, Sadler MC, Tashkin DP. Mentholated cigarette use and lung cancer. *Archives of internal medicine.* 1995; 155:727–32. [PubMed: 7695461]
20. Carpenter CL, Jarvik ME, Morgenstern H, McCarthy WJ, London SJ. Mentholated cigarette smoking and lung-cancer risk. *Ann Epidemiol.* 1999; 9:114–20. [PubMed: 10037555]
21. Kabat GC, Hebert JR. Use of mentholated cigarettes and oropharyngeal cancer. *Epidemiology.* 1994; 5:183–8. [PubMed: 8172993]
22. Hebert JR, Kabat GC. Menthol cigarette smoking and oesophageal cancer. *Int J Epidemiol.* 1989; 18:37–44. [PubMed: 2722381]
23. Hsu PC, Lan RS, Brasky TM, Marian C, Cheema AK, Resson HW, et al. Metabolomic profiles of current cigarette smokers. *Mol Carcinog.* 2016
24. Benowitz NL, Zevin S, Jacob P 3rd. Suppression of nicotine intake during ad libitum cigarette smoking by high-dose transdermal nicotine. *J Pharmacol Exp Ther.* 1998; 287:958–62. [PubMed: 9864279]
25. Perez-Stable EJ, Herrera B, Jacob P 3rd, Benowitz NL. Nicotine metabolism and intake in black and white smokers. *JAMA : the journal of the American Medical Association.* 1998; 280:152–6. [PubMed: 9669788]
26. Tautenhahn R, Patti GJ, Rinehart D, Siuzdak G. XCMS Online: a web-based platform to process untargeted metabolomic data. *Anal Chem.* 2012; 84:5035–9. [PubMed: 22533540]
27. Perez-Stable EJ, Benowitz NL, Marin G. Is serum cotinine a better measure of cigarette smoking than self-report? *Prev Med.* 1995; 24:171–9. [PubMed: 7597020]
28. Giovino GA, Sidney S, Gfroerer JC, O'Malley PM, Allen JA, Richter PA, et al. Epidemiology of menthol cigarette use. *Nicotine Tob Res.* 2004; 6(Suppl 1):S67–81. [PubMed: 14982710]
29. Cubbin C, Soobader MJ, LeClere FB. The intersection of gender and race/ethnicity in smoking behaviors among menthol and non-menthol smokers in the United States. *Addiction.* 2010; 105(Suppl 1):32–8. [PubMed: 21059134]
30. Samet JM, Benowitz NL, Clanton MS, Connolly GN, DeLeeuw KL, Hamm LA, et al. Menthol Cigarettes and Public Health: Review of the Scientific Evidence and Recommendations. Mar 23.2011
31. Gust SW, Pickens RW, Pechacek TF. Relation of puff volume to other topographical measures of smoking. *Addict Behav.* 1983; 8:115–9. [PubMed: 6613709]
32. Epstein LH, Dickson BE, Ossip DJ, Stiller R, Russell PO, Winter K. Relationships among measures of smoking topography. *Addict Behav.* 1982; 7:307–10. [PubMed: 7180627]
33. Marian C, O'Connor RJ, Djordjevic MV, Rees VW, Hatsukami DK, Shields PG. Reconciling human smoking behavior and machine smoking patterns: implications for understanding smoking behavior and the impact on laboratory studies. *Cancer Epidemiol Biomarkers Prev.* 2009; 18:3305–20. [PubMed: 19959678]
34. Perkins KA, Karelitz JL, Giedgowd GE, Conklin CA. The reliability of puff topography and subjective responses during ad lib smoking of a single cigarette. *Nicotine Tob Res.* 2012; 14:490–4. [PubMed: 22039077]
35. Ahijevych K, Parsley LA. Smoke constituent exposure and stage of change in black and white women cigarette smokers. *Addict Behav.* 1999; 24:115–20. [PubMed: 10189978]
36. Jarvik ME, Tashkin DP, Caskey NH, McCarthy WJ, Rosenblatt MR. Mentholated cigarettes decrease puff volume of smoke and increase carbon monoxide absorption. *Physiology & behavior.* 1994; 56:563–70. [PubMed: 7972409]
37. McCarthy WJ, Caskey NH, Jarvik ME, Gross TM, Rosenblatt MR, Carpenter C. Menthol vs nonmenthol cigarettes: effects on smoking behavior. *Am J Public Health.* 1995; 85:67–72. [PubMed: 7832264]
38. Nil R, Battig K. Separate effects of cigarette smoke yield and smoke taste on smoking behavior. *Psychopharmacology (Berl).* 1989; 99:54–9. [PubMed: 2506604]

39. Ahijevych K, Gillespie J, Demirci M, Jagadeesh J. Menthol and nonmenthol cigarettes and smoke exposure in black and white women. *Pharmacol Biochem Behav.* 1996; 53:355–60. [PubMed: 8808144]
40. Miller GEJ, ME, Caskey NH, Segerstrom SC, Rosenblatt MR, McCarthy WJ. Cigarette mentholation increases smokers' exhaled carbon monoxide levels. *Exp Clin Psychopharmacol.* 1994; 2:154–60.
41. Strasser AA, Lerman C, Sanborn PM, Pickworth WB, Feldman EA. New lower nicotine cigarettes can produce compensatory smoking and increased carbon monoxide exposure. *Drug Alcohol Depend.* 2007; 86:294–300. [PubMed: 16930853]
42. Strasser AA, Ashare RL, Kaufman M, Tang KZ, Mesaros AC, Blair IA. The effect of menthol on cigarette smoking behaviors, biomarkers and subjective responses. *Cancer Epidemiol Biomarkers Prev.* 2013; 22:382–9. [PubMed: 23334588]
43. Caskey NH, Jarvik ME, McCarthy WJ, Rosenblatt MR, Gross TM, Carpenter CL. Rapid smoking of menthol and nonmenthol cigarettes by black and white smokers. *Pharmacol Biochem Behav.* 1993; 46:259–63. [PubMed: 8265679]
44. Miller GEJ, ME, Caskey NH, Segerstrom SC, Rosenblatt MR, McCarthy WJ. Cigarette Mentholation Increases Smokers' Exhaled Carbon Monoxide Levels. *Experimental and Clinical Psychopharmacology.* 1994; 2:154–60.
45. Ahijevych K, Parsley LA. Smoke constituent exposure and stage of change in black and white women cigarette smokers. *Addict Behav.* 1999; 24:115–20. [PubMed: 10189978]
46. Patterson F, Benowitz N, Shields P, Kaufmann V, Jepson C, Wileyto P, et al. Individual differences in nicotine intake per cigarette. *Cancer Epidemiol Biomarkers Prev.* 2003; 12:468–71. [PubMed: 12750245]
47. Ahijevych K, Gillespie J, Demirci M, Jagadeesh J. Menthol and nonmenthol cigarettes and smoke exposure in black and white women. *Pharmacol Biochem Behav.* 1996; 53:355–60. [PubMed: 8808144]
48. Clark PI, Gautam S, Gerson LW. Effect of menthol cigarettes on biochemical markers of smoke exposure among black and white smokers. *Chest.* 1996; 110:1194–8. [PubMed: 8915220]
49. Pickworth WB, Moolchan ET, Berlin I, Murty R. Sensory and physiologic effects of menthol and non-menthol cigarettes with differing nicotine delivery. *Pharmacol Biochem Behav.* 2002; 71:55–61. [PubMed: 11812507]
50. Heck JD. A review and assessment of menthol employed as a cigarette flavoring ingredient. *Food and chemical toxicology : an international journal published for the British Industrial Biological Research Association.* 2010; 48(Suppl 2):S1–38.
51. Ahijevych K, Garrett BE. Menthol pharmacology and its potential impact on cigarette smoking behavior. *Nicotine Tob Res.* 2004; 6(Suppl 1):S17–28. [PubMed: 14982706]
52. Ferris Wayne G, Connolly GN. Application, function, and effects of menthol in cigarettes: a survey of tobacco industry documents. *Nicotine Tob Res.* 2004; 6(Suppl 1):S43–54. [PubMed: 14982708]
53. Gelal A, Jacob P 3rd, Yu L, Benowitz NL. Disposition kinetics and effects of menthol. *Clinical pharmacology and therapeutics.* 1999; 66:128–35. [PubMed: 10460066]
54. Benowitz NL, Dains KM, Dempsey D, Havel C, Wilson M, Jacob P 3rd. Urine menthol as a biomarker of mentholated cigarette smoking. *Cancer Epidemiol Biomarkers Prev.* 2010; 19:3013–9. [PubMed: 20962297]
55. Spichiger M, Muhlbauer RC, Brenneisen R. Determination of menthol in plasma and urine of rats and humans by headspace solid phase microextraction and gas chromatography--mass spectrometry. *Journal of chromatography B, Analytical technologies in the biomedical and life sciences.* 2004; 799:111–7. [PubMed: 14659442]
56. Hiki N, Kaminishi M, Hasunuma T, Nakamura M, Nomura S, Yahagi N, et al. A phase I study evaluating tolerability, pharmacokinetics, and preliminary efficacy of L-menthol in upper gastrointestinal endoscopy. *Clinical pharmacology and therapeutics.* 2011; 90:221–8. [PubMed: 21544078]
57. Muller DC, Degen C, Scherer G, Jahreis G, Niessner R, Scherer M. Metabolomics using GC-TOF-MS followed by subsequent GC-FID and HILIC-MS/MS analysis revealed significantly altered fatty acid and phospholipid species profiles in plasma of smokers. *Journal of chromatography B,*

- Analytical technologies in the biomedical and life sciences. 2014; 966:117–26. [PubMed: 24630914]
58. Wang-Sattler R, Yu Y, Mittelstrass K, Lattka E, Altmaier E, Gieger C, et al. Metabolic profiling reveals distinct variations linked to nicotine consumption in humans--first results from the KORA study. *PLoS one*. 2008; 3:e3863. [PubMed: 19057651]
 59. Xu T, Holzapfel C, Dong X, Bader E, Yu Z, Prehn C, et al. Effects of smoking and smoking cessation on human serum metabolite profile: results from the KORA cohort study. *BMC medicine*. 2013; 11:60. [PubMed: 23497222]
 60. Bernhardt G, Biersack B, Bollwein S, Schobert R, Zoldakova M. Terpene conjugates of diaminedichloridoplatinum(II) complexes: antiproliferative effects in HL-60 leukemia, 518A2 melanoma, and HT-29 colon cancer cells. *Chem Biodivers*. 2008; 5:1645–59. [PubMed: 18729100]
 61. Kim SH, Nam JH, Park EJ, Kim BJ, Kim SJ, So I, et al. Menthol regulates TRPM8-independent processes in PC-3 prostate cancer cells. *Biochimica et biophysica acta*. 2009; 1792:33–8. [PubMed: 18955132]
 62. Dresser GK, Wachter V, Wong S, Wong HT, Bailey DG. Evaluation of peppermint oil and ascorbyl palmitate as inhibitors of cytochrome P4503A4 activity in vitro and in vivo. *Clinical pharmacology and therapeutics*. 2002; 72:247–55. [PubMed: 12235445]
 63. Seo KA, Kim H, Ku HY, Ahn HJ, Park SJ, Bae SK, et al. The monoterpenoids citral and geraniol are moderate inhibitors of CYP2B6 hydroxylase activity. *Chemico-biological interactions*. 2008; 174:141–6. [PubMed: 18611395]
 64. Yano JK, Denton TT, Cerny MA, Zhang X, Johnson EF, Cashman JR. Synthetic inhibitors of cytochrome P-450 2A6: inhibitory activity, difference spectra, mechanism of inhibition, and protein cocrystallization. *J Med Chem*. 2006; 49:6987–7001. [PubMed: 17125252]
 65. Munder PG, Modolell M, Andreesen R, Weltzien HU, Westphal O. Lysophosphatidylcholine (Lysolecithin) and its Synthetic Analogues. *Immunomodulating and Other Biologic Effects*. Springer Seminars in Immunopathology. 1979; 2:187–203.
 66. Mehta D. Lysophosphatidylcholine: an enigmatic lysolipid. *American journal of physiology Lung cellular and molecular physiology*. 2005; 289:L174–5. [PubMed: 16002999]
 67. Haley JE, Stefano GB, Catapane EJ. Correlation between acidic phospholipids and serotonin and between lysolecithin and dopamine in ganglia of the marine mussel, *Mytilus edulis*. *Experientia*. 1978; 34:210–2. [PubMed: 624353]
 68. Ryborg AK, Johansen C, Iversen L, Kragballe K. Lysophosphatidylcholine induces keratinocyte differentiation and upregulation of AP-1- and NF-kappaB DNA-binding activity. *Acta dermatovenereologica*. 2004; 84:433–8. [PubMed: 15844632]
 69. Perrin-Cocon L, Agaugue S, Coutant F, Saint-Mezard P, Guironnet-Paquet A, Nicolas JF, et al. Lysophosphatidylcholine is a natural adjuvant that initiates cellular immune responses. *Vaccine*. 2006; 24:1254–63. [PubMed: 16229929]
 70. Aiyar N, Disa J, Ao Z, Ju H, Nerurkar S, Willette RN, et al. Lysophosphatidylcholine induces inflammatory activation of human coronary artery smooth muscle cells. *Molecular and cellular biochemistry*. 2007; 295:113–20. [PubMed: 16896535]
 71. Rikitake Y, Kawashima S, Yamashita T, Ueyama T, Ishido S, Hotta H, et al. Lysophosphatidylcholine inhibits endothelial cell migration and proliferation via inhibition of the extracellular signal-regulated kinase pathway. *Arteriosclerosis, thrombosis, and vascular biology*. 2000; 20:1006–12.
 72. Sakai M, Miyazaki A, Hakamata H, Sasaki T, Yui S, Yamazaki M, et al. Lysophosphatidylcholine plays an essential role in the mitogenic effect of oxidized low density lipoprotein on murine macrophages. *The Journal of biological chemistry*. 1994; 269:31430–5. [PubMed: 7989310]
 73. Gillett MP, Besterman EM. Plasma concentrations of lysolecithin and other phospholipids in the healthy population and in men suffering from atherosclerotic diseases. *Atherosclerosis*. 1975; 22:111–24. [PubMed: 1156468]
 74. Drobnik W, Liebisch G, Audebert FX, Frohlich D, Gluck T, Vogel P, et al. Plasma ceramide and lysophosphatidylcholine inversely correlate with mortality in sepsis patients. *Journal of lipid research*. 2003; 44:754–61. [PubMed: 12562829]

75. Frisardi V, Panza F, Seripa D, Farooqui T, Farooqui AA. Glycerophospholipids and glycerophospholipid-derived lipid mediators: a complex meshwork in Alzheimer's disease pathology. *Progress in lipid research*. 2011; 50:313–30. [PubMed: 21703303]
76. Farooqui AA, Horrocks LA, Farooqui T. Glycerophospholipids in brain: their metabolism, incorporation into membranes, functions, and involvement in neurological disorders. *Chemistry and physics of lipids*. 2000; 106:1–29. [PubMed: 10878232]
77. Kwatia MA, Doyle CB, Cho W, Enhorning G, Ackerman SJ. Combined activities of secretory phospholipases and eosinophil lysophospholipases induce pulmonary surfactant dysfunction by phospholipid hydrolysis. *The Journal of allergy and clinical immunology*. 2007; 119:838–47. [PubMed: 17321580]
78. Andersson DA, Nash M, Bevan S. Modulation of the cold-activated channel TRPM8 by lysophospholipids and polyunsaturated fatty acids. *The Journal of neuroscience : the official journal of the Society for Neuroscience*. 2007; 27:3347–55. [PubMed: 17376995]
79. Gentry C, Stoakley N, Andersson DA, Bevan S. The roles of iPLA2, TRPM8 and TRPA1 in chemically induced cold hypersensitivity. *Mol Pain*. 2010; 6:4. [PubMed: 20092626]
80. Canales L, Chen J, Kelty E, Musah S, Webb C, Pisano MM, et al. Developmental cigarette smoke exposure: liver proteome profile alterations in low birth weight pups. *Toxicology*. 2012; 300:1–11. [PubMed: 22609517]
81. Weng DY, Chen J, Taslim C, Hsu PC, Marian C, David SP, et al. Persistent alterations of gene expression profiling of human peripheral blood mononuclear cells from smokers. *Mol Carcinog*. 2015

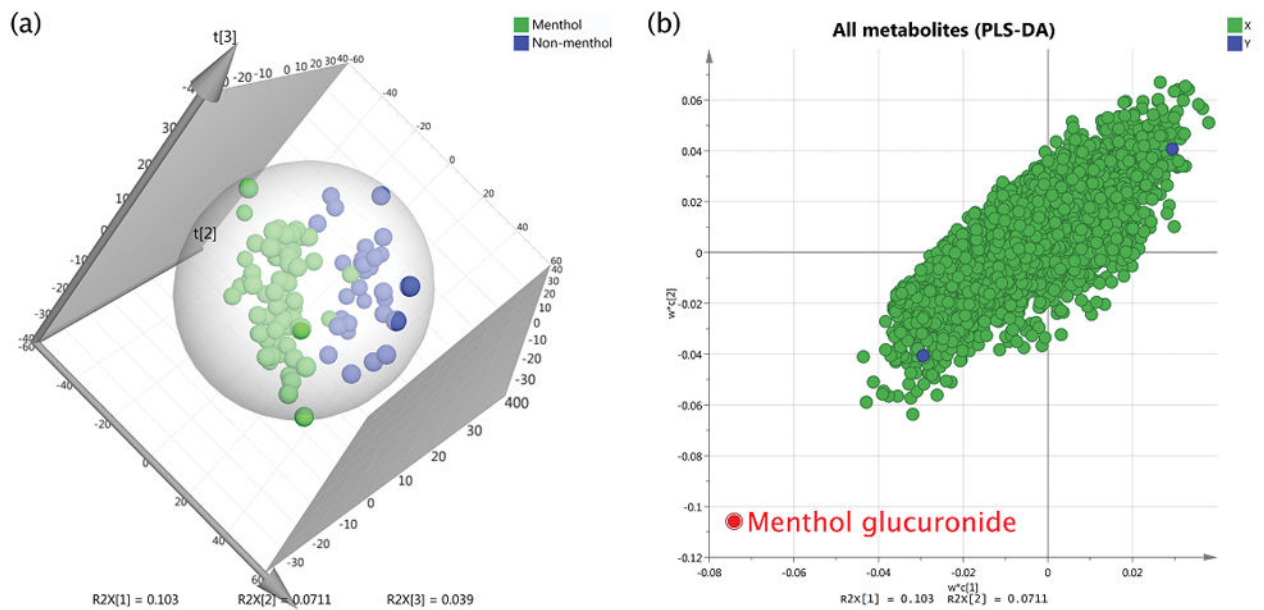


Figure 1. Partial Least Squares-Discriminant Analysis (PLS-DA) of all menthol and non-menthol cigarette smokers. a) 3D score plot between the selected principle components (PCs) showed difference between menthol (green) and non-menthol (blue) smokers in their metabolomic profiles. b) Loadings plot showed menthol glucuronide as the most influential metabolite discriminating metabolome of menthol and non-menthol smokers with an ANOVA assessment of the cross-validated (CV) P value of 0.0003. The p-value indicates the probability level where a model with this F-value may be the result of just chance.

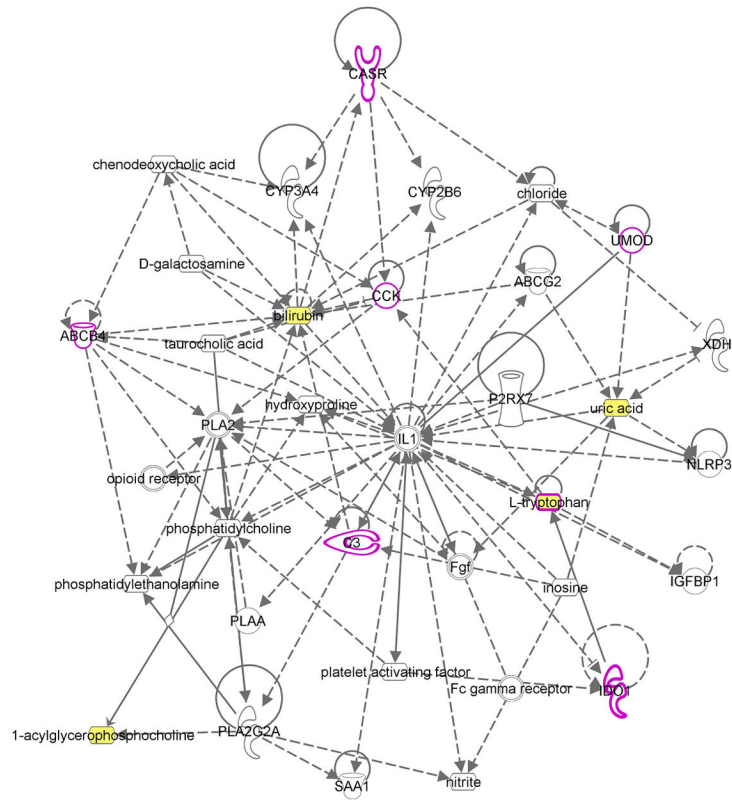


Figure 2. Network associated with menthol boosts in menthol smokers. Yellow nodes represented metabolites mapped from our study. Seven molecules known as biomarkers for cancer were outlined in magenta.

Table 1

Study participant characteristics and differences between menthol and non-menthol smokers.

Variable	All (n=105)		Menthol (n=71, 67.6%)		Non-menthol (n=34, 32.4%)		<i>p</i> ^d
	n (%)	Mean ± SD	n (%)	Mean ± SD	n (%)	Mean ± SD	
Age (y)		43.1 ± 9.6		43.8 ± 9.3		41.4 ± 10.9	0.25
Age (y), categorical							
< 44 yrs-old	55 (52.4)		34 (47.9)		21 (61.8)		0.18
44 yrs-old	50 (47.6)		37 (52.1)		13 (38.2)		
Gender							
Male	67 (63.8)		43 (60.6)		24 (70.6)		0.32
Female	38 (36.2)		28 (39.4)		10 (29.4)		
Race ^b							< 0.00001
AA	63 (60.0)		58 (81.7)		5 (14.7)		
EA	38 (36.2)		12 (16.9)		26 (76.5)		
Biracial	4 (3.8)		1 (1.4)		3 (8.8)		
Yrs smoked (y)		22.9 ± 9.9		22.5 ± 9.8		23.7 ± 10.3	0.57
Yrs smoked (y), categorical							
< 22 yrs	52 (49.5)		39 (54.9)		13 (38.2)		0.11
22 yrs	53 (50.5)		32 (45.1)		21 (61.8)		
Plasma cotinine (ng/ml)		252.6 ± 103.3		247.5 ± 97.3		263.4 ± 115.6	0.46
Plasma cotinine, categorical							
Low (<200)	35 (33.3)		23 (32.4)		12 (35.3)		0.96
Medium (200–279)	35 (33.3)		24 (33.8)		11 (32.4)		
High (> 279)	35 (33.3)		24 (33.8)		11 (32.4)		
NMR		0.38 ± 0.22		0.37 ± 0.24		0.41 ± 0.17	0.44
NMR, categorical							
Q1 (< 0.238)	25 (23.8)		20 (28.2)		5 (14.7)		0.25
Q2 (0.238–0.34)	27 (25.7)		19 (26.8)		8 (23.5)		
Q3 (0.341–0.458)	27 (25.7)		18 (25.4)		9 (26.5)		
Q4 (> 0.458)	26 (24.8)		14 (19.7)		12 (35.3)		
FTND scoring ^c		5.0 ± 2.3		4.8 ± 2.1		5.4 ± 2.7	0.20

Variable	All (n=105)		Menthol (n=71, 67.6%)		Non-menthol (n=34, 32.4%)		<i>p</i> ^a
	n (%)	Mean ± SD	n (%)	Mean ± SD	n (%)	Mean ± SD	
FTND scoring, categorical							
< 5 points	44 (41.9)		32 (45.1)		12 (35.3)		0.31
5-6 points	33 (31.4)		23 (32.4)		10 (29.4)		
> 6 points	27 (25.7)		15 (21.1)		12 (35.3)		

^a *p*-values represent differences in menthol vs. non-menthol smokers for each characteristic. Continuous variables were evaluated by two-sample t-tests (*Italic*), and chi square (X^2) tests were used to investigate the differences in distributions of categorical variables from menthol to non-menthol smokers.

^b AA: African-Americans, EA: European Americans.

^c FTND: Fagerstrom Test for Nicotine Dependence.

Table 2

Correlation of the 2nd MG boost to smoking-related variables.

	All smokers		Menthol		Non-menthol	
	r^1	p^2	r	p	r	p
Average puff volume (ml)	0.36	0.0003	0.48	6.22E-05	0.09	0.64
CO boost	0.31	0.001	0.22	0.06	0.47	0.006
Average puff duration (sec)	0.30	0.003	0.33	0.008	0.10	0.58
Total smoke exposure (ml)	0.26	0.01	0.35	0.004	0.14	0.46
Nicotine boost	0.26	0.04	0.32	0.05	0.28	0.19
Average inter-puff interval (sec)	-0.14	0.17	-0.37	0.002	0.27	0.14
Number of puffs	0.11	0.27	0.17	0.18	0.07	0.69
Cotinine (ng/ml)	0.05	0.61	0.18	0.12	-0.15	0.40
Maximum puff velocity (ml/sec)	0.05	0.62	0.18	0.14	0.16	0.38
FTND	0.04	0.65	0.22	0.06	0.02	0.90
3HC (ng/ml)	0.04	0.69	0.23	0.06	-0.11	0.54
NMR	0.01	0.90	0.13	0.27	0.04	0.84

Data significant at $p < 0.05$.

^{1,2} r and p were computed based on Spearman's rank correlation coefficient.

Table 3

Differences in the smoking-related characteristics of participant from self-reported menthol and non-menthol smokers in the study.

	Menthol (71)	Non-menthol (34)	<i>p</i> [*]	Fold Change (Menthol/Non-menthol)
	Mean ± SD	Mean ± SD		
MG boost	31.2 ± 42.8	-2.78 ± 18.3	2.31E-05	11.2
Maximum puff velocity (ml/sec)	47.5 ± 13.7	51.6 ± 16.1	0.20	-1.1
FTND	4.8 ± 2.1	5.4 ± 2.7	0.20	-1.1
CO boost	5.2 ± 3.1	4.4 ± 3.6	0.20	1.2
3HC (ng/ml)	90.8 ± 67.9	106.7 ± 62.7	0.25	-1.2
Nicotine boost	14.0 ± 8.6	11.9 ± 7.0	0.31	1.2
NMR	0.4 ± 0.2	0.4 ± 0.2	0.44	-1.1
Average puff volume (ml)	55.7 ± 18.5	52.7 ± 18.0	0.45	1.1
Average puff duration (sec)	1.8 ± 0.6	1.6 ± 0.8	0.46	1.1
Cotinine (ng/ml)	247.5 ± 97.3	263.4 ± 115.6	0.46	-1.1
Average inter-puff interval (sec)	20.0 ± 12.7	21.0 ± 14.7	0.74	-1.0
Number of puffs	12.6 ± 7.5	12.3 ± 6.6	0.87	1.0
Total smoke exposure (ml)	691.7 ± 455.9	690.3 ± 547.8	0.99	1.0

* *p*-value was computed based on two sample t tests. Data significant at *p* < 0.05.

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Table 4

Known metabolites significantly correlated with MG boost among 71 menthol smokers.

m/z	RT	Metabolites	Adducts	Category	ppm	q-value	PartialCorr
331.18	3.07	Menthol-glucuronide	[M-H]−	Prenol lipids	1	0.0040	0.53
640.29	5.52	S-(PGA2)-glutathione	[M-H]−	Carboxylic acids and derivatives	1	0.0042	-0.52
231.00	1.70	2,4-Dihydroxyacetophenone 5-sulfate	[M-H]−	Benzene and substituted derivatives	6	0.0199	0.42
205.10	0.36	L-Tryptophan	[M+H]+	Indoles and derivatives	8	0.0288	0.53
167.02	0.34	Uric acid	[M-H]−	Alkaloids and derivatives	7	0.0344	0.39
187.01	1.71	Benzyl sulfate	[M-H]−	Organic sulfuric acids and derivatives	5	0.0344	0.42
462.30	5.01	PC(O-12:0/O-1:0)	[M+Na]+	Glycerophospholipids	4	0.0344	-0.54
799.48	4.65	Thalicoside A	[M+H]+	Terpenoids	7	0.0344	-0.54
460.28	4.63	PE(P-16:0/0:0)	[M+Na]+	Glycerophospholipids	6	0.0364	-0.54
185.08	4.74	2-(1-Ethoxyethoxy)propanoic acid	[M+Na]+	Carboxylic acids and derivatives	7	0.0397	-0.53
585.27	3.95	Bilirubin	[M+H]+	Tetrapyrroles and derivatives	0	0.0408	0.52
189.00	1.71	Oxalosuccinic acid	[M-H]−	Carboxylic acids and derivatives	2	0.0472	0.41
792.60	8.48	PC(O-16:0/22:6)	[M+H]+	Glycerophospholipids	8	0.0480	0.49
567.27	4.87	2-deoxy-20-hydroxyecdysone 22-phosphate	[M+H]+	Sterol lipids	0	0.0485	-0.50
240.10	4.73	N-Ornithyl-L-taurine	[M+H]+	Carboxylic acids and derivatives	3	0.0491	-0.49
313.27	4.85	10-oxo-nonadecanoic acid	[M+H]+	Fatty acyls	0	0.0491	-0.51
481.32	5.00	20-hydroxyecdysone	[M+H]+	Sterol lipids	2	0.0491	-0.52
505.35	5.03	Isothiankunic acid	[M+H]+	Prenol lipids	7	0.0491	-0.51
834.60	8.73	PC(22:2/16:1)	[M+Na]+	Glycerophospholipids	1	0.0491	0.45
544.34	5.03	LysoPC(20:4)	[M+H]+	Glycerophospholipids	0	0.0498	-0.48

* q-value (corrected p-value) was computed based on two-way ANCOVA model adjusted for gender, race and cotinine levels. PartialCorr represents the correlation between 2nd MG boost and the metabolites.