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OBSERVATIONAL STUDY

Epigenetic Modifications in the Biology of Nonalcoholic Fatty Liver Disease

The Role of DNA Hydroxymethylation and TET Proteins

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Abstract: The 5-Hydroxymethylcytosine (5-hmC) is an epigenetic modification whose role in the pathogenesis of metabolic-related complex diseases remains unexplored; 5-hmC appears to be prevalent in the mitochondrial genome. The Ten-Eleven-Translocation (TET) family of proteins is responsible for catalyzing the conversion of 5-methylcytosine to 5-hmC. We hypothesized that epigenetic editing by 5-hmC might be a novel mechanism through which nonalcoholic fatty liver disease (NAFLD)-associated molecular traits could be explained.

Hence, we performed an observational study to explore global levels of 5-hmC in fresh liver samples of patients with NAFLD and controls (n = 90) using an enzyme-linked-immunosorbent serologic assay and immunohistochemistry. We also screened for genetic variation in TET 1–3 loci by next generation sequencing to explore its contribution to the disease biology. The study was conducted in 2 stages (discovery and replication) and included 476 participants.

We observed that the amount of 5-hmC in the liver of both NAFLD patients and controls was relatively low (up to 0.1%); a significant association was found with liver mitochondrial DNA copy number (R = 0.50, P = 0.000382) and *PPARGC1A*-mRNA levels (R = −0.57, P = 0.04).

We did not observe any significant difference in the 5-hmC nuclear immunostaining score between NAFLD patients and controls; nevertheless, we found that patients with NAFLD (0.4 ± 0.5) had significantly lower nonnuclear-5-hmC staining compared with controls (1.8 ± 0.8), means ± standard deviation, P = 0.028. The missense p.Ile1123Met variant (*TET1*-rs3998860) was significantly associated with serum levels of caspase-generated CK-18 fragment-cell death biomarker in the discovery and replication stage, and the disease severity (odds ratio: 1.47, 95% confidence interval: 1.10–1.97; P = 0.005). The p.Ile1762-Val substitution (*TET2*-rs2454206) was associated with liver *PPARGC1A*-methylation and transcriptional levels, and Type 2 diabetes.

Our results suggest that 5-hmC might be involved in the pathogenesis of NAFLD by regulating liver mitochondrial biogenesis and *PPARGC1A* expression. Genetic diversity at *TET* loci suggests an ''epigenetic'' regulation of programmed liver-cell death and a TET-mediated fine-tuning of the liver *PPARGC1A*-transcriptional program.

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Abbreviations: 5-hmC = 5-hydroxymethylcytosine, CK-18 = caspase-generated CK-18 fragment, mtDNA = mitochondrial DNA, NAFLD = nonalcoholic fatty liver disease, nDNA = nuclear DNA, NGS = next generation sequencing, NNLH = near-normal liver histology, PPARGC1A = peroxisome proliferator-activated receptor gamma coactivator 1α, TET = Ten-Eleven-Translocation.

INTRODUCTION

Nonalcoholic fatty liver disease (NAFLD) is a highly prevalent chronic liver disease[1] that is clustered in the metabolic syndrome (MetS) along with other cardiometabolic comorbidities.[2–4] In fact, NAFLD is not only a component of the diagnostic criteria for MetS but is critically involved in the development of insulin resistance.[5,6]

The clinical picture of NAFLD might present in a relatively mild form, characterized by abnormal hepatic triglyceride accumulation, named simple or bland steatosis or nonalcoholic fatty liver (NAFL). However, it might progress to a more severe clinical condition, named nonalcoholic steatohepatitis (NASH), which is characterized by fat accumulation accompanied by liver cell injury, a mixed inflammatory lobular infiltrate, and

variable fibrosis.[7,8] Notably, NAFL is not necessarily associated with a benign prognosis.[9] A recent meta-analysis showed that patients with NAFL could develop liver fibrosis over time.[10] In addition, NAFL may seriously increase the probability of exacerbating associated co-morbidities, including cardiovascular disease.[11]

Like many other complex diseases, NAFLD is under both genetic and environmental influences.[12] Recent evidence from human studies indicates presence of tissue-specific epigenetic modifications in both nuclear[6,13,14] and mitochondrial (mt) genome.[15] These are involved not only in NAFLD pathogenesis and histological disease progression but are relevant to the pathophysiology of the MetS-associated phenotypes.[6,15] Furthermore, there is compelling evidence showing that mitochondrial function,[15–19] and mitochondrial DNA (mtDNA) copy number are both diminished in NAFLD.[6] Notably, the aforementioned molecular changes are not only determinants of the disease prognosis and severity[6,14,15,20] and even the potential development of liver cancer[14] but are also critical modifiers of disease-associated metabolic traits.[6,15] In fact, we previously demonstrated that epigenetic modifications occurring in the liver of patients with NAFLD, such as methylation of target sites (dinucleotides CpG) in the promoter of the peroxisome proliferator-activated receptor gamma coactivator 1α (*PPARGC1A*, a master transcription factor involved in liver-related metabolic pathways, including mitochondrial biogenesis and fatty acid oxidation, gluconeogenesis, and lipogenesis) adversely affect peripheral insulin sensitivity.[6] Finally, we and others have previously shown that liver epigenetic changes are not necessarily stable but subject to reversion.[13,15]

The 5-hydroxymethylcytosine (5-hmC) is an old,[21] but recently rediscovered and understood epigenetic modification that modulates gene transcription by influencing putative DNA demethylation and chromatin structure remodelling.[22] Interestingly, 5-hmC profile seems to be tissue-specific[23] and is highly dependent on the cellular state, resulting in changes in response to environmental stimuli and metabolic perturbations.[24] Non-CG hydroxymethylation appears to be prevalent in the mitochondrial genome as well.[25,26]

The Ten-Eleven-Translocation (TET1, TET2, and TET3) family of proteins, which share significant sequence homology at their C-terminal catalytic domains, were recently identified as 5mC hydrolases that catalyze the conversion of 5-mC to 5-hmC.[27] These proteins, which frequently mutate in cancer, are involved in programmed cell death in neurons.[28] However, whether this effect could be observed in hepatocytes remains unknown.

Because NAFLD is associated with altered DNA methylation profiles, changes in mtDNA content and *PPARGC1A* expression, we hypothesized that epigenetic editing by 5-hmC might be a novel mechanism through which the NAFLD-associated molecular traits could be explained. Hence, we explored the global levels of 5-hmC in the liver of patients with NAFLD at different stages of disease severity and controls. In addition, we screened for genetic variation in *TET* 1–3 loci by targeted next generation sequencing (NGS) to explore its contribution to the disease biology.

PATIENTS AND METHODS

Study Design and Patient Selection

This study was conducted in 3 phases: an initial study that included exploration of global levels of 5-hmC in the liver of patients with NAFLD (n = 67) and control subjects (n = 23);

screening of genetic variation of *TET1*, *TET2*, and *TET3* by targeted NGS in a discovery group of 96 individuals (64 NAFLD patients and 32 controls); and independent replication of selected single nucleotide polymorphisms (SNPs) in a case–control association study (n = 380 participants).

Patients were included in the study if there was histopathological evidence of NAFLD, either NAFL or NASH, based on a liver biopsy (LB) conducted within the study period. Exclusion criteria were secondary causes of steatosis, including alcohol abuse (≥30 g alcohol daily for men and ≥20 g for women), total parenteral nutrition, hepatitis B and hepatitis C virus infection, and the use of drugs known to precipitate steatosis. By using standard clinical and laboratory evaluation, as well as LB features when applicable, autoimmune liver disease, metabolic liver disease, Wilson's disease, and α-1-antitrypsin deficiency were likewise ruled out in all patients.

Healthy subjects were selected for inclusion into the control group if their age and sex matched those of the NAFLD patients and in whom, in addition to the standard health assessment described below, a careful ultrasonographic (US) examination of the liver was performed to exclude fatty liver infiltration. In addition, controls were included at any study phase if they did not exhibit features of MetS and did not have fatty liver at liver US.

For obvious ethical reasons, the control subjects were not exposed to the potential risk of an LB; hence, in explorations that involved molecular studies requiring fresh liver tissue, patients with near-normal liver histology (NNLH) were included. In the NNLH subjects, LB was justified owing to the presence of persistently mildly elevated serum activity of liver enzymes. In all NNLH subjects, all causes of common liver disease were ruled out, and these patients were included in the study if they did not present either histological evidence of fatty change or necrotic-inflammatory activity, and had either minimal changes or mild cholestasis as histological diagnosis.

The case participants and the controls were selected during the same study period from the same population of patients attending the liver unit, and all shared the same demographic characteristics.

Ethics, Consent, and Permissions

Human serum and DNA samples from healthy individuals and those diagnosed with NAFLD, as well as liver biopsies from all the patients, were obtained with written informed consent following Institutional Review Board-approved protocols (protocol number: 104/HGAZ/09, 89/100, and 1204/2012, Comite de Bioetica Hospital Abel Zubizarreta). All the investigations performed in this study were conducted in accordance with the guidelines of the 1975 Declaration of Helsinki.

Physical, Anthropometric, and Biochemical Evaluation

Health examinations included anthropometric measurements, a questionnaire on health-related behaviors, and biochemical determinations.

Caspase-generated CK-18 fragment (CK-18)—a noninvasive quantification of hepatocellular apoptosis[29]—concentration was measured by the 1-step in vitro immunoassay M30-apoptosense enzyme-linked-immunosorbent serologic assay (ELISA) kit (PEVIVA AB; DiaPharma, OH) that selectively recognizes the caspase-generated fragments of keratin 18 containing the K18Asp396 neoepitope (CK-18).

Anthropometric measurements and blood samples were obtained from each patient at the time of LB or DNA sample collection, and before any intervention. Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Liver Biopsy and Histopathological Evaluation

LB was performed before any intervention with ultrasound guidance and a modified 1.4 mm-diameter Menghini needle (Hepafix, Braun, Germany) under local anesthesia, in the outpatient setting. A portion of each LB specimen was routinely fixed in 40 g/L formaldehyde (pH 7.4) embedded in paraffin before being stained with hematoxylin and eosin, Masson trichrome, and silver impregnation for reticular fibers. All the biopsies were at least 3 cm in length and contained a minimum of 8 portal tracts. The liver biopsies were read by a single experienced hepatopathologist, who was blinded to all the clinical and laboratory data. The degree of steatosis was assessed according to the system developed by Kleiner et al.[30] NASH was defined as steatosis, accompanied by mixed inflammatory-cell infiltration, hepatocyte ballooning and necrosis, glycogen nuclei, Mallory's hyaline, and any stage of fibrosis, including absent fibrosis.[31] Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Liver Immunohistochemistry

Immunostaining for TET1 protein and 5-hmC was performed on liver specimens previously obtained from NAFLD patients and controls and included in paraffin before use. Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Electron Microscopy of the Liver Tissue

Electron microscopy (EM) studies were performed on liver specimens by immersion of a small sample (1 mm) in 2.5% glutaraldehyde and 0.1 M phosphate buffer (pH 7.4). Sections were mounted in copper grids, counterstained with lead citrate, and observed in a transmission electronic microscope (Carl Zeiss, Carl-Zeiss-Straße 56, 73447 Oberkochen, Germany). Further details are provided in extant literature.[15]

RNA Preparation and Real-Time RT-PCR for Quantitative Assessment of mRNA Expression and Bisulfite Treatment of DNA for Methylation-Specific PCR

Total RNA was prepared from liver tissue using phenol extraction step method, with an additional DNAse digestion. Genomic DNA was isolated from liver biopsies at the same time as RNA by standard methods, and DNA bisulfite modification was performed as previously reported.[6] Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400, which includes details on reverse transcription polymerase chain reaction (RT-PCR), data normalization, and the primer sequences.

Global Liver 5-hmC Quantification

We measured global 5-hmC levels in the DNA isolated from fresh liver specimens of patients and controls using Quest 5-hmC DNA ELISA Kit (Zymo Research, Irvine, CA) according to the manufacturer's instructions. This system is highly sensitive to 5-hmC DNA and has a detection threshold of 0.02% per 100 ng input DNA. In brief, 5-hmC was detected using a sandwich-based ELISA kit that includes a control DNA set, which was calibrated to accurately quantify the percent 5-hmC in sample DNA by a standard curve. All samples were measured in triplicate, allowing us to estimate the mean % 5-hmC level. The % 5-hmC levels were not normally distributed and were thus log-transformed for statistical analyses.

Characterization of Genetic Variation in *TET 1–3* by NGS

NGS technology was employed to search for the presence of genetic variation in *TET1–3* loci covering all protein-coding exons (*TET1*: 9.7 kb, 12 exons, *TET2*: 19 kb, 13 exons, and *TET3*: 11 kb, 9 exons), in addition to exon–intron boundaries and 5′ and 3′ UTR regions, which were examined by semi-conductor technology offered in the Ion Torrent PGM system (IT-PGM) (Life Technologies, Carlsbad, CA) using a 316 chip. All reagents were obtained from the same provider. Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Variant Calling, Estimation of Quality Control, Data Analysis, and Prediction of Variant/ Mutation Effect

Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Replication Study: Genotype and Association Analysis, Power and Sample Size Calculation, and Population Stratification

The genetic analyses were performed on genomic DNA extracted from white blood cells. Genotyping of the *TET1*-rs3998860 (p.Ile1123Met) and *TET2*-rs2454206 (p.Ile1762Val) was performed using a TaqMan genotyping assay (dbSNP rs3998860 assay C_2719530_10 and dbSNP rs2454206 assay C_11566753_20; Applied Biosystems, Carlsbad, CA) according to the manufacturer's instructions.

Using the CaTS power calculator for genetic association studies[32] and assuming a prevalence of NAFLD of 0.30, an minor allele frequency of ∼0.3, and a relative risk of ∼2, our sample had 100% power for the additive genetic model and 98% for the dominant 1. Complete details are provided in the Supplemental Content, http://links.lww.com/MD/A400.

Quantification of Liver mtDNA Copy Number

An assay based on real-time quantitative PCR was used for both nuclear DNA (nDNA) and mtDNA quantification using SYBR Green as a fluorescent dye (Invitrogen, Carlsbad, CA 92008, USA) as previously described.[6] Primer sequences are shown in Supplemental Content, http://links.lww.com/MD/A400, along with further details on quantification of liver mtDNA copy number.

Statistical Analysis

Quantitative data were expressed as mean ± standard deviation (SD) unless otherwise indicated. Because significant differences in variance were observed between the groups in most of the variables and the distribution was significantly skewed in most cases, we chose to be conservative and assessed the differences between the groups by using nonparametric Mann–Whitney U or Kruskal–Wallis tests. As indicated, in some comparisons, log-transformed variables were compared by analysis of variance and Neuman–Keuls test for mean

differences, as in the case of liver 5-hmC levels, liver methylation and mRNA expression of *PPARGC1A*, and serum CK-18 levels. Univariate correlations were obtained via the Spearman's rank correlation test. For association tests between genotypes or allele frequencies and phenotypes, such as liver disease and Type 2 diabetes, Cochran–Armitage test for trend, or logistic regression were employed.

The CSS/Statistica program package version 6.0 (StatSoft, Tulsa, OK) was employed in the aforementioned analyses.

RESULTS

Clinical and biochemical features of the entire population in each of the study phases are shown in Tables 1–3. Overall, patients with NAFLD had all the features of the MetS, including abdominal obesity, insulin resistance, hypertriglyceridemia, and arterial hypertension.

Global Liver DNA Hydroxymethylation Levels Are Significantly Associated With Liver mtDNA Content and the Abundance of *PPARGC1A*-mRNA

First, we explored the association between liver 5-hmC levels and NAFLD as a disease trait. The findings revealed no differences in the overall mean levels of global DNA hydroxymethylation in subjects with NNLH (0.100 ± 0.016) and patients with NAFLD (0.095 ± 0.034), $P =$ NS. The overall median (interquartile range, IQR) levels of global DNA hydroxymethylation were 0.101% (IQR: 0.035) and 0.094% (IQR: 0.052) for subjects with NNLH and NAFLD, respectively.

The analysis of global liver 5-hmC levels and NAFLD disease severity did not show significant differences either (NAFL: $0.090 \pm 0.035\%$ vs NASH: $0.100 \pm 0.032\%$, mean, SD, $P =$ NS), and the same conclusion was reached for liver fibrosis (F0–F1: $0.10 \pm 0.032\%$ vs F2–F4: $0.094 \pm 0.034\%$, $P =$ NS).

To explore the localization pattern of 5-hmC, we further evaluated the liver specimens (stained by immunohistochemistry [IHQ], by a specific antibody) of NAFLD patients and subjects with NNLH. While the immunoreactivity product of 5-hmC was preferentially localized in the nucleus of hepatocytes in both controls and NAFLD patients, with no significant differences in staining intensity, there were remarkable differences in both the pattern of nonnuclear localization and the immunostaining counts. The immunoreactivity product of 5-hmC in subjects with NNLH was randomly located in nonnuclear (cytoplasmic) areas of hepatocytes, showing a granular pattern. Conversely, in patients with NAFLD, 5-hmC was preferentially localized at the edge of lipid-laden hepatocytes (Figure 1). Notably, liver specimens of patients with NAFLD were examined by EM and showed mitochondria in close physical association with large lipid droplets (Figure 1)—a finding that supports a putative localization of the nonnuclear immunoreactivity product of 5-hmC in mtDNA. Further

TABLE 1. Clinical and Biochemical Characteristics of Subjects With Near Normal Liver Histology (NNLH) and Patients With NAFLD Included in the Exploration of Liver Global Levels of DNA 5-Hydroxymethylation

Variables (Mean $\pm$ SD)	NNLH	NAFL	NASH	*P* Value[*] (*P*<)	*P* Value[**] (*P*<)	*P* Value[***] (*P*<)
Number of subjects	23	31	36	—	—	—
Age, y	47 ± 9	51 ± 8	48.0 ± 8.7	NS	NS	NS
BMI, kg/m^2	25.5 ± 3.9	31.5 ± 5.0	32.3 ± 6.0	0.00008	0.000032	NS
Waist circumference, cm	91 ± 16	104.0 ± 8.4	107 ± 13	0.027	0.004	NS
Fasting plasma glucose, mg/dL	88.4 ± 11.7	98 ± 13	104 ± 12	0.014	0.000036	NS
Fasting plasma insulin, μU/mL	5.9 ± 1.4	14.5 ± 10.0	15.0 ± 9.5	0.00001	0.000036	NS
HOMA-IR index	1.2 ± 0.3	3.4 ± 2.0	3.9 ± 2.6	0.000005	0.000014	NS
SABP, mm Hg	116 ± 19	124 ± 13	126.0 ± 13.5	0.06	0.04	NS
DABP, mm Hg	72 ± 11	77 ± 13	78.4 ± 8.5	NS	NS	NS
Total cholesterol, mg/dL	202 ± 41	204 ± 36	218 ± 49	NS	NS	NS
Triglycerides, mg/dL	145 ± 97	153 ± 68	209 ± 136	NS	0.03	NS
AST, U/L	48.5 ± 37.0	36 ± 16	39 ± 22	NS	NS	NS
ALT, U/L	74 ± 70	59 ± 39	59 ± 36	NS	NS	NS
GGT, U/L	110 ± 106	77 ± 83	61 ± 39	0.02	0.01	NS
AP, U/L	259 ± 169	232 ± 123	171 ± 68	NS	0.06	0.04
Histological features						
Degree of steatosis, %	—	45 ± 27	60.6 ± 21.0	—		0.01
Lobular inflammation (0–3)	—	0.5 ± 0.6	0.9 ± 0.6	—	—	0.008
Portal inflammation (0–2)	—	0	1.5 ± 0.6	—	—	0.000001
Hepatocellular ballooning (0–2)	—	0	1.00 ± 0.46	—	—	0.000001
Fibrosis stage	—	0	1.5 ± 0.6	—	—	0.000001
NAS	—	2.4 ± 1.3	5.8 ± 1.8	—	—	0.000001

ALT and AST = serum alanine and aspartate aminotransferase, respectively; AP = alkaline phosphatase; BMI = body mass index; GGT = gamma-glutamyl-transferase; HOMA-IR = homeostatic model assessment-insulin resistance; NAFL = nonalcoholic fatty liver or simple steatosis; NAFLD = nonalcoholic fatty liver disease; NASH = nonalcoholic steatohepatitis; NNLH = near-normal liver histology and abnormal liver enzymes; NS = nonsignificant; SABP and DABP = systolic and diastolic arterial blood pressure, respectively; SD = standard deviation.
[*] NNLH vs NAFL comparisons.
[**] Comparisons between NNLH vs NASH.
[***] Comparisons between NAFL and NASH subjects. The *P* value pertains to the statistical significance calculated using Mann–Whitney *U* test.

TABLE 2. Clinical and Biochemical Characteristics of Control Subjects and Patients With NAFLD Included in the Discovery Group of the Exploration of *TET 1−3* Genetic Variation by Next Generation Sequencing

Variables (Mean ± SD)	Control Subjects	NAFL	NASH	P Value* (P<)	P Value** (P<)	P Value*** (P<)
Number of subjects	32	32	32	—	—	—
Age, yr	48.0 ± 7.4	51.9 ± 9.8	51.2 ± 11.0	NS	NS	NS
BMI, kg/m^2	23.0 ± 2.4	31.6 ± 4.7	36.0 ± 5.6	1.0×10^{-8}	1.0×10^{-8}	0.003
Waist circumference, cm	80.0 ± 9.1	101.0 ± 8.6	112 ± 14	1.0×10^{-8}	1.0×10^{-8}	0.001
Fasting plasma glucose, mg/dL	81.3 ± 7.2	96.5 ± 19.0	127 ± 49	0.0002	1.0×10^{-8}	0.002
Fasting plasma insulin, μU/mL	5.3 ± 2.4	12.4 ± 6.5	20.9 ± 13.6	1.0×10^{-8}	1.0×10^{-8}	0.0007
HOMA-IR index	1.0 ± 0.5	3 ± 2	6.2 ± 4.6	1.0×10^{-8}	1.0×10^{-8}	0.0001
SABP, mm Hg	116 ± 9.2	125.0 ± 11.5	133.0 ± 16.4	0.021	0.0008	NS
DABP, mm Hg	72.5 ± 8.6	79 ± 8	79.0 ± 14.6	0.025	0.01	NS
Total cholesterol, mg/dL	219 ± 51	208 ± 59	207 ± 46	NS	NS	NS
Triglycerides, mg/dL	87 ± 30	149 ± 77	221 ± 142	0.01	0.008	NS
AST, U/L	21.5 ± 4.4	38 ± 19	49.4 ± 33.0	0.001	0.0007	NS
ALT, U/L	21.3 ± 5.0	69 ± 101	60 ± 35	0.001	0.0007	NS
GGT, U/L	36 ± 26	48.0 ± 29.5	86 ± 82	NS	0.039	0.03
AP, U/L	160 ± 67	220 ± 89	269 ± 92	0.04	0.01	0.03
CK18 levels	129 ± 90	243 ± 202	355 ± 284	NS	0.03	NS
Histological features						
Degree of steatosis, %	—	49 ± 23	60 ± 20	—	—	0.05
Lobular inflammation (0−3)	—	0.6 ± 0.5	1.4 ± 0.5	—	—	0.001
Portal inflammation (0−2)	—	0	1.7 ± 0.7	—	—	1.0×10^{-8}
Hepatocellular ballooning (0−2)	—	0	0.7 ± 0.6	—	—	0.002
Fibrosis stage	—	0.1 ± 0.5	1.9 ± 1.2	—	—	1.0×10^{-8}
NAS	—	2.4 ± 1.0	6.4 ± 1.6	—	—	1.0×10^{-8}

ALT and AST = serum alanine and aspartate aminotransferase, respectively; BMI = body mass index; GGT = gamma-glutamyl-transferase; AP = alkaline phosphatase; HOMA-IR = homeostatic model assessment-insulin resistance; NAFL = nonalcoholic fatty liver or simple steatosis; NAFLD = nonalcoholic fatty liver disease; NASH = nonalcoholic steatohepatitis; NS = nonsignificant; SABP and DABP = systolic and diastolic arterial blood pressure, respectively; SD = standard deviation.
*NNLH vs NAFL comparisons.
**Comparisons between NNLH vs NASH.
***Comparisons between NAFL and NASH subjects. The P value pertains to the statistical significance calculated using Mann−Whitney U test.

analysis on nonnuclear immunostaining scores showed significant differences between patients with NAFLD (0.4 ± 0.5) and controls (1.8 ± 0.8), P = 0.028.

We next examined crude linear trends in the association of global liver DNA hydroxymethylation with continuous phenotypic variables, including age, body mass index (BMI), percent body fat, waist circumference, homeostatic model assessment-insulin resistance (HOMA-IR), and ALT and AST (serum alanine and aspartate aminotransferase, respectively) liver enzyme levels, as well as continuous molecular traits of interest associated with NAFLD, including expression levels of *PPARGC1A*-mRNA and liver mtDNA copy number. Of note, we found a positive and significant correlation between liver 5-hmC levels and liver mtDNA content (Spearman R = 0.50, P = 0.000382) (Figure 1), and an inverse and significant association with the abundance of liver *PPARGC1A*-mRNA (Spearman R = −0.57, P = 0.04). As previously reported,[6] patients with NAFLD have a significantly lower liver mtDNA copy number, expressed as an mtDNA/nDNA ratio (62.5 ± 41.0), in comparison with subjects with NNLH (103.5 ± 88.0).

In addition, a significant and inverse correlation of liver 5-hmC levels was found with ALT (Spearman R = −0.24, P = 0.02) and AST (Spearman R = −0.28, P = 0.01) serum levels, and BMI (Spearman R = −0.27, P = 0.01).

Analysis of Missense Variation in *TET1* and *TET2* Loci Shows Association With NAFLD-Disease Biology and Type 2 Diabetes

TET proteins play a significant role in the generation of 5-hmC; in fact, these enzymes mediate the conversion of 5-mC to 5-hmC utilizing oxygen and 2-ketoglutarate as substrates.

To understand the potential contribution of genetic variation in *TET1−3* loci in NAFLD-associated molecular traits, including changes in promoter methylation levels of *PPARGC1α*, we followed an NGS approach, which was applied to all the exons, exon−intron unions and 5' and 3' untranslated regions of these genes. Furthermore, based on the previous knowledge of *TET*-mutations are able to mediate cell death,[28] we explored the role of variants on surrogate markers of hepatocellular apoptosis (release of caspase-cleaved cytokeratin-18, CK-18)[29] and the disease severity.

In the exploratory study, we generated more than 2 million reads with an average length of 145 bases of quality equal to or exceeding Q20, and a coverage on average higher than 100×. Overall, analysis of sequence data yielded 28 SNPs in *TET1* gene, 37 in *TET2*, and 24 in *TET3*; according to the information pertaining to the dbSNP or the 1000 genomes, among these, 23 were novel variants.

TABLE 3. Clinical and Biochemical Characteristics of Control Subjects and Patients With NAFLD in the Independent Replication Study of the Exploration of *TET 1–3* Genetic Variation

Variables (Mean ± SD)	Control Subjects	NAFL	NASH	P Value* (P<)	P Value** (P<)	P Value*** (P<)
Number of subjects	135	103	142	—	—	—
Age, yr	48 ± 12	53.6 ± 10.0	51.8 ± 11.0	NS	NS	NS
BMI, kg/m^2	25 ± 4	31.6 ± 5.5	33.0 ± 5.7	1.0×10^{-8}	1.0×10^{-8}	0.009
Waist circumference, cm	84 ± 16	103.0 ± 15.4	108 ± 13	1.0×10^{-8}	1.0×10^{-8}	0.001
Fasting plasma glucose, mg/dL	81.0 ± 13.6	98 ± 20	130 ± 122	1.0×10^{-8}	1.0×10^{-8}	1.0×10^{-8}
Fasting plasma insulin, μU/mL	7.0 ± 4.7	12.9 ± 8.0	16.4 ± 11.0	1.0×10^{-8}	1.0×10^{-8}	0.003
HOMA-IR index	1.4 ± 1.0	3.1 ± 2.0	5.3 ± 6.8	1.0×10^{-8}	1.0×10^{-8}	0.00008
SABP, mm Hg	115 ± 14	125.4 ± 14.0	128 ± 16	1.0×10^{-8}	1.0×10^{-8}	NS
DABP, mm Hg	71.5 ± 9.4	77 ± 11	79 ± 12	1.0×10^{-8}	1.0×10^{-8}	NS
Total cholesterol, mg/dL	209 ± 42	205 ± 48	210 ± 43	NS	NS	NS
Triglycerides, mg/dL	114 ± 79	152 ± 74	192 ± 121	0.0005	1.0×10^{-8}	0.04
AST, U/L	18.7 ± 24.0	35 ± 17	51 ± 33	0.00001	1.0×10^{-8}	0.00001
ALT, U/L	17 ± 45	57 ± 63	72 ± 55	0.000001	1.0×10^{-8}	0.0003
GGT, U/L	24 ± 69	66 ± 58	86 ± 86	0.0002	1.0×10^{-8}	0.04
AP, U/L	140 ± 118	233 ± 101	227 ± 113	0.000006	0.0001	NS
CK18 levels	136 ± 93	230 ± 231	312 ± 259	NS	0.03	0.04
Histological features						
Degree of steatosis, %	—	48 ± 26	60 ± 21	—	—	0.0003
Lobular inflammation (0–3)	—	0.6 ± 0.6	1.2 ± 0.6	—	—	1.0×10^{-8}
Portal inflammation (0–2)	—	0	1.50 ± 0.66	—	—	1.0×10^{-8}
Hepatocellular ballooning (0–2)	—	0	0.8 ± 0.6	—	—	1.0×10^{-8}
Fibrosis stage	—	0	1.5 ± 1.3	—	—	1.0×10^{-8}
NAS	—	2.7 ± 1.1	5.9 ± 1.5	—	—	1.0×10^{-8}

ALT and AST = serum alanine and aspartate aminotransferase, respectively; AP = alkaline phosphatase; BMI = body mass index; GGT = gamma-glutamyl-transferase; HOMA-IR = homeostatic model assessment-insulin resistance; NAFL = nonalcoholic fatty liver or simple steatosis; NAFLD = nonalcoholic fatty liver disease; NASH = nonalcoholic steatohepatitis; NS = nonsignificant; SABP and DABP = systolic and diastolic arterial blood pressure, respectively; SD = standard deviation.
* NNLH vs NAFL comparisons.
** Stands for comparisons between NNLH vs NASH.
*** Comparisons between NAFL and NASH subjects. The P value pertains to the statistical significance calculated using Mann–Whitney U test.

Information of genetic variation took precedence over nonsynonymous SNPs (those that change the amino acid sequence). Distribution of the variants' function is depicted in the Supplemental Content, http://links.lww.com/MD/A400. As can be seen, a high percentage of genetic variation of *TET1* (35.5%) and *TET2* (27%) were missense variants. The main features of variants selected for the replication study, including chromosome location and predicted functional consequences, are shown in Supplemental Content, http://links.lww.com/MD/A400.

The association analysis in the exploratory study showed that *TET1*-rs3998860 (p.Ile1123Met) was significantly associated with serum levels of CK-18 (P = 0.003; Figure 2). Replication analysis performed on the larger validation set confirmed the initial findings, indicating that hepatocytes of NAFLD patients who are homozygous for the G allele are more susceptible to apoptosis compared with carriers of the ancestral A allele (P = 0.001). Accordingly, an allelic test showed that the variant was significantly associated with the disease severity (Cochran–Armitage test for trend P = 0.005); generalized odds ratio (OR): 1.47, 95% confidence interval (CI): 1.10 to 1.97 for G vs A allele as a reference. Genotype distribution was in Hardy–Weinberg equilibrium (P = 0.49).

To gain insights into the putative mechanisms by which this variant might influence the disease phenotype, we next used IHQ to explore the level of liver TET1 expression according to rs3998860 genotypes. We observed that TET1 immunoreactivity product significantly (P = 0.036) increased in subjects carrying at least 1 copy of the A allele (AA and AG), in comparison with carriers of the rs3998860-GG genotype (Figure 2).

On the other hand, we aimed to analyze whether genetic variation in *TET1–3* loci plays any role in the modulation of liver *PPARGC1α* transcriptional activity. The association analysis of sequence variation in the exploratory study showed that p.Ile1762Val substitution (*TET2*-rs2454206), located in exon 11, was significantly associated with the liver promoter methylation status of *PPARGC1α* (methylated DNA/unmethylated DNA ratio: AA: 0.61 ± 0.1 vs AG + GG: 1.6 ± 0.4, mean ± SD, P = 0.03 on log transformed values), indicating that G allele carriers have higher levels of promoter methylation compared with homozygous AA.

To further assess whether this variant has any effect on liver gene expression of *PPARGC1α*, we explored the abundance of the transcript according to the variant genotypes in a sub-sample of the replication set that had available isolated liver mRNA (n = 66). In line with the findings observed in the discovery stage, we found that rs2454206 was significantly associated with the relative abundance of liver *PPARGC1α*-mRNA in both the dominant (P = 0.005) and additive (P = 0.018) model of inheritance (Figure 3), suggesting that
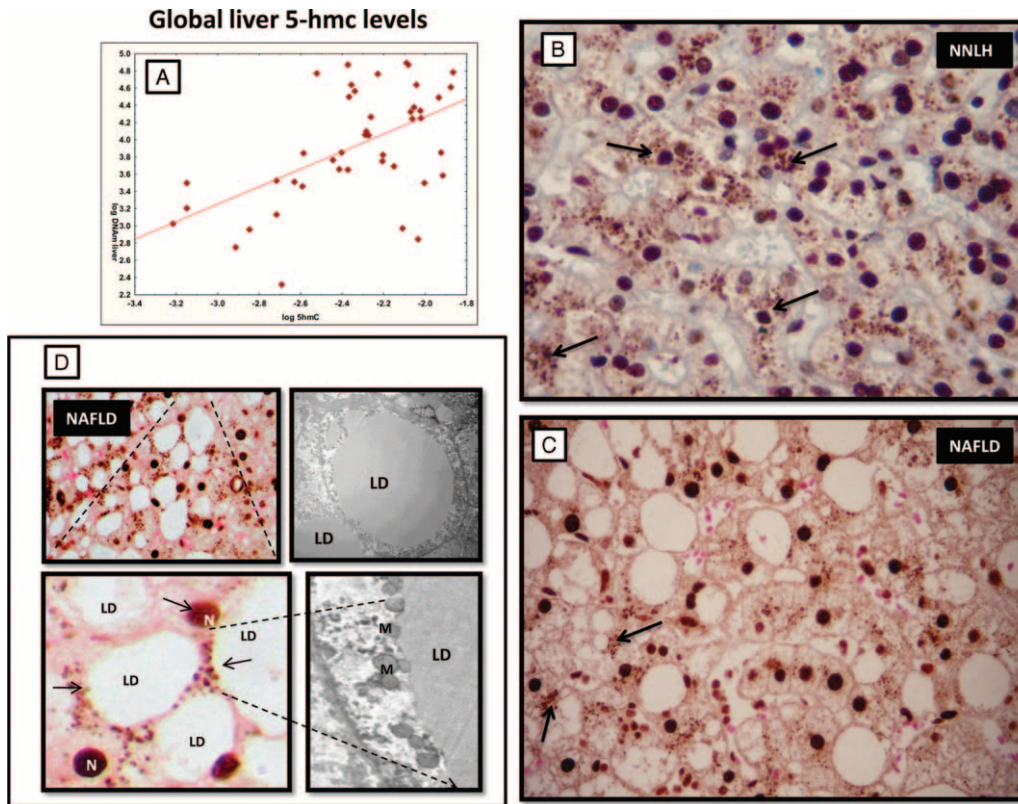
FIGURE 1. Global levels of 5-hydroxymethylcytosine (5-hmC) in the liver tissue of patients with NAFLD and near normal liver histology (NNLH). A: Correlation between log-transformed liver mtDNA/nDNA ratio and log-transformed global liver 5-hmC levels measured by a sandwich-based enzyme-linked immunosorbent assay employing an anti-5-hydroxymethylcytosine polyclonal antibody. B and C: A representative specimen of immunostaining for 5-hmC in the liver of a patient with NNLH and NAFLD, respectively. Arrows indicate nonnuclear areas of 5-hmC staining. D: Magnification shows 5-hmC preferentially localized at the edge of lipid-laden hepatocytes; N = nucleus. Representative electron micrograph of hepatocyte isolated from an NASH patient showing a lipid droplet (LD) and mitochondria (M) in close physical association with LDs. Magnification: ×3000. 5-hmC immunoreactivity was examined using light microscopy of liver sections, while counterstaining was performed with eosin. Original magnification: ×400. NAFLD = nonalcoholic fatty liver disease.

carriers of the G allele have decreased liver expression of *PPARGC1α*. Collectively, our findings suggest that the p.Ile1762Val substitution would be involved in the modulation of liver *PPARGC1α* methylation profile, thereby regulating gene transcription.

To gain insights into possible clinical implications of this finding, and based on previous knowledge showing that liver expression of *PPARGC1α* modulates insulin resistance,[6] we explored the association between the variant and the presence of Type 2 diabetes in the entire replication set. Notably, we observed a significant association between the rs2454206 and Type 2 diabetes, chi-square 10.37, $P = 0.00128$ (OR 1.60 per G allele, 95% CI: 1.01–2.51; Figure 3). The genotype distribution was in Hardy–Weinberg equilibrium ($P = 0.91$).

DISCUSSION

Epigenetic modifications, including changes in the DNA methylation/demethylation rate, are involved in the pathogenesis of complex diseases, including NAFLD. It is known that tissue levels of 5-hmC are variable, and are higher in embryonic pluripotent stem cells and cells of neuronal lineages, compared to adult tissue.[33–35] In addition, high 5-hmC levels are a feature of rapidly proliferating cell populations. Nevertheless, 5-hmC

level in the liver of patients with NAFLD presently remains unknown.

In this study, we aimed to explore global levels of 5-hmC in the liver of patients with NAFLD at different stages of disease severity, aiming to better understand its role in the disease biology. In agreement with a recent study, whereby the authors measured global 5-hmC levels in nonneoplastic liver tissue of patients with hepatocellular carcinoma,[36] the amount of 5-hmC in the liver of patients with NAFLD, as well as in the liver of subjects with NNLH, was relatively low (up to 0.1%). These findings were confirmed by immunohistostaining of liver sections with specific anti-5hmC antibody.

Furthermore, while no differences in the global level of liver 5-hmC between patients and controls were observed, a significant association was found with molecular traits of interest, suggesting the possibility of an involvement of hydroxylation of mC in the development of NAFLD. For instance, we could demonstrate a significant association between liver 5-hmC and liver mtDNA copy number. Previous work in which the authors used mtDNA immunoprecipitation by an antibody directed against 5-hmC supports our findings, showing substantial 5-hmC levels in the mtDNA.[25,26] It is noteworthy to highlight that a major limitation of all current methodologies that measure global DNA hydroxymethylation stems from their
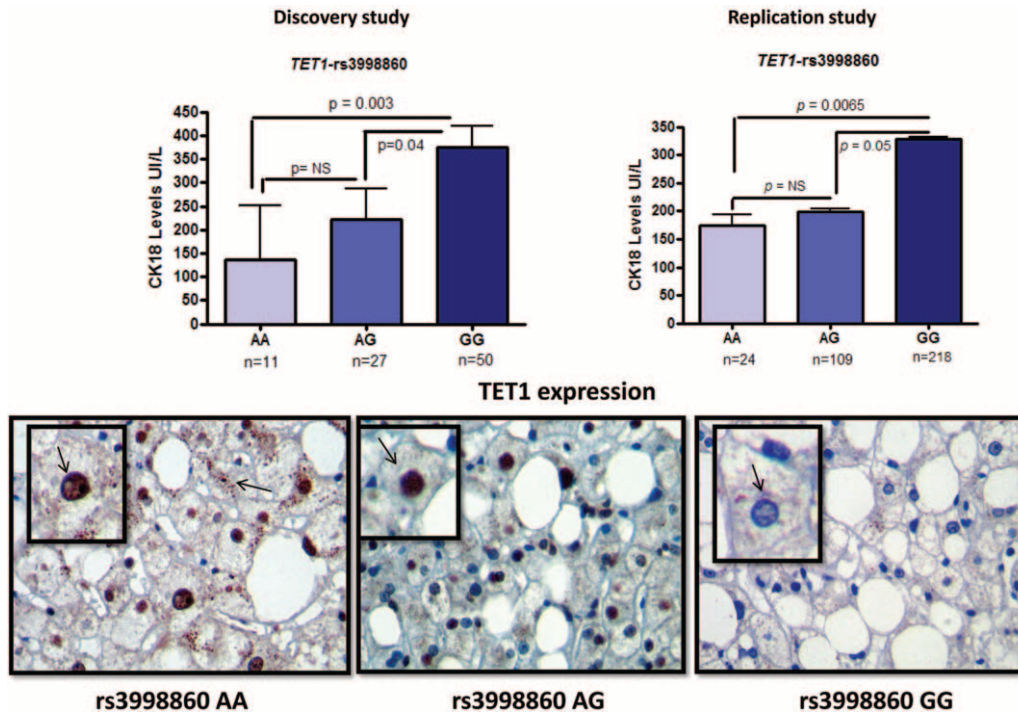
FIGURE 2. Association analysis of *TET1*-rs3998860 (p.Ile1123Met) and serum CK-18 levels. Upper panels: Results of the association analysis of rs3998860 and serum CK-18 cell death biomarker levels in the discovery and replication stage, left and right, respectively; caspase-mediated cleavage of the CK-18 reflects degradation of the intracellular cytoskeleton when cells undergo apoptosis. Each bar represents the mean ± standard error value. *P* values pertain to log-transformed serum CK-18 levels, analyzed by analysis of variance. Lower panels: Representative specimens of immunostaining for liver TET1 protein expression evaluated by immunohistochemistry, according to *TET1*-rs3998860 genotypes. Counterstaining was performed using hematoxylin. Original magnification: ×400.

inability to provide information on whether 5-hmC occurs in the nuclear or mt genome. Moreover, none provides information about locus localization in the genome. Nevertheless, we were able to show that oxidation of mC to hmC is a process that occurs not only in the nucleus of liver cells but outside them. In fact, the cytosolic localization of liver 5-hmC by immunostaining strongly suggests mitochondrial localization as extrachromosomal DNA, which is any DNA that is found outside of the nucleus of a cell, corresponds exclusively to mtDNA. While our immunohistochemical analysis revealed no differences in the nuclear 5-hmC staining scores between patients with NAFLD and controls, we observed that NAFLD was associated with a significant decrease of nonnuclear 5-hmC suggesting that mtDNA has different hydroxymethylation levels according to the disease status.

It is currently unknown whether members of the TET family are able to target liver mtDNA, as in vitro explorations in HeLa and 3T3-L1 cells found TET1 and TET2, or only TET1, respectively, in the mitochondrial fraction, suggesting that the TET-mtDNA interaction is very much cell-type dependent.[26] Thus, we cannot rule out the possibility of an interaction between 5-hmC and liver mtDNA involving a large regulatory network, including genes that regulate mitochondrial biogenesis, replication and transcription. The significant association between liver levels of 5-hmC and liver mtDNA content allows us to hypothesize that epigenetic editing by hydroxymethylation is involved in the regulation of liver mtDNA copy number. Hydroxymethylated cytosines within the human mtDNA control region (D-loop), as demonstrated in previous

work,[26] strongly support the biological plausibility of our findings.

In addition, we observed that global 5-hmC levels in the liver were negatively associated with the abundance of liver *PPARGC1A*-mRNA. This finding suggests that the balance between hypomethylation and hypermethylation in this locus modulates its transcriptional activity, as we previously reported by exploring targeted regions of the gene promoter.[6] In fact, the capacity to convert 5-mC into 5-hmC is very much influenced by the initial amount of 5-mC, which was shown to be higher in the liver of NAFLD patients.[6]

On the other hand, we observed that a missense p.Ile1123-Met variant located in *TET* methylcytosine dioxygenase 1 (rs3998860) was significantly associated with serum levels of the CK-18 cell death biomarker. In addition, empirical evidence indicated that caspase-mediated cleavage of the keratin 18 reflects degradation of the intracellular cytoskeleton when cells undergo apoptosis.[37] This finding was replicated in the validation sample, in which the rs3998860-G allele was significantly associated with the disease severity, suggesting an involvement of *TET1* locus in the modulation of apoptosis and liver injury in NAFLD. Exploration of a putative functional role of rs3998860 revealed that immunostaining scores of liver TET1 were significantly reduced in homozygous carriers of the G allele. While previous evidence indicated that the effects of TET1 overexpression on gene transcription are unrelated to its 5-mC dioxygenase function[33] TET1-mediated DNA demethylation provides protection against oxidative stress in neuronal cells.[28] In effect, knockdown of *tet1* in cerebellar granule cells
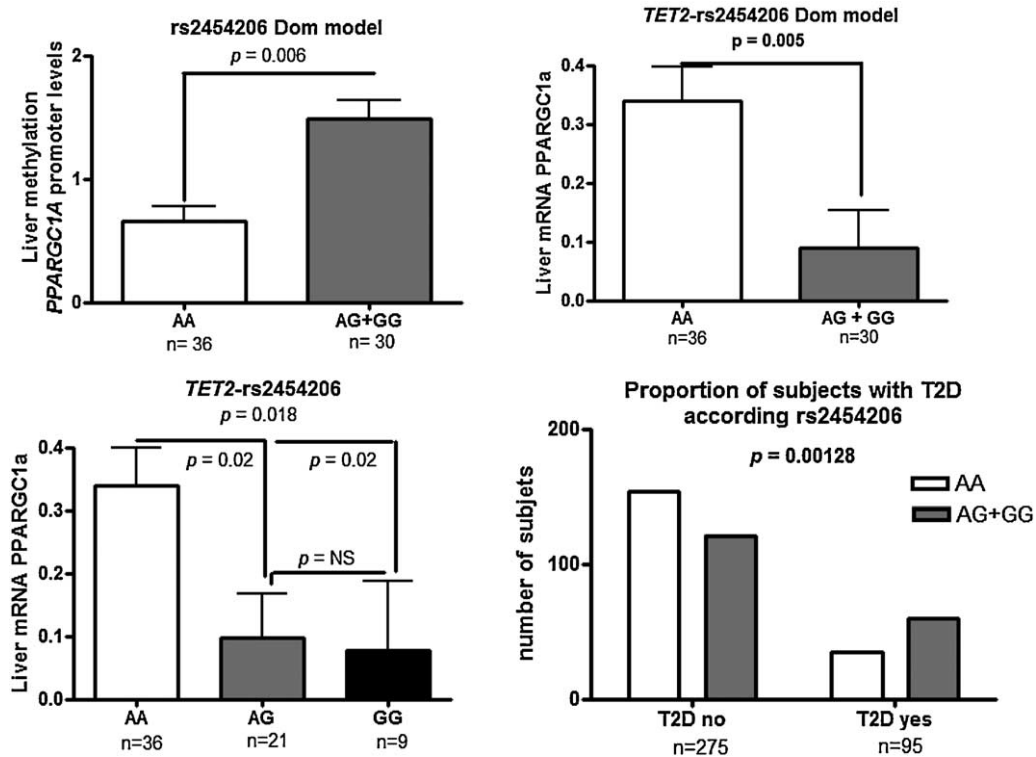
FIGURE 3. Association analysis of *TET2*-rs2454206 (p.Ile1762Val) and liver methylation and the transcriptional status of the coactivator *PPARGC1A* (peroxisome proliferator-activated receptor gamma coactivator 1α). Upper panel: Methylated DNA/unmethylated DNA ratio for the liver *PPARGC1A* promoter according to rs2454206 and liver abundance of *PPARGC1A* mRNA evaluated by quantitative real-time PCR genotypes in the dominant model of inheritance. Bottom panel: Liver abundance of *PPARGC1A* mRNA evaluated by quantitative real-time PCR according to rs2454206 genotypes in the additive model of inheritance, and the distribution of the variant genotypes according to the presence or absence of Type 2 diabetes in the entire replication set. Each bar represents the mean ± standard error value. In each sample, the abundance of target genes was normalized to the amount of cyclophilin to carry out comparisons between the groups. *P* values apply to log-transformed values of liver *PPARGC1A* promoter methylation and mRNA levels. PCR = polymerase chain reaction.

in mice significantly increases apoptosis by promoting neuronal cell death induced by oxidative stress.[28]

Finally, we observed that the p.Ile1762Val substitution (*TET2*-rs2454206) was significantly associated with liver *PPARGC1A* methylation and transcriptional levels. This finding suggests that the *TET2* locus might be involved in the modulation of the liver *PPARGC1A* methylation/demethylation balance, putatively in response to the metabolic cellular environment. More importantly, this molecular trait would influence the development of Type 2 diabetes, suggesting new avenues in the understanding of the genetic susceptibility to diseases that cluster in the metabolic syndrome.

Of note, we were not able to find any significant association between global liver 5-hmC levels and genetic variation in *TET*-locus; neither we were able to find an association between *TET*-variants and mtDNA copy number. Nevertheless, previous evidence suggest that the dynamics of DNA methylation/demethylation is governed by a complex interaction of proteins, including isocitrate dehydrogenases (IDHs) that catalyze the oxidative decarboxylation of isocitrate to 2-oxoglutarate, which is a substrate of TET proteins.[38] For instance, it was recently reported that the expression levels of both IDH1 and IDH2 regulate the total 5-hmC content in the adult liver.[38] Furthermore, as explained before, it cannot be ascertained whether mitochondrial 5-hmC is a product of the same enzymatic reaction that takes place in the nucleus, as there is not

conclusive evidence of the expression of TET proteins in the mitochondria. Hence, further research is required to guarantee a deep understanding of the regulatory mechanisms by which 5-hmC levels are modulated in NAFLD, and so, what are the mechanisms by which this epigenetic modification regulates gene expression. Remarkably, IDH-proteins localize to the mitochondrial matrix and have activity as NADP-dependent IDH either cytosolic or peroxisomal; the later of particular significance as NAFLD severity is associated with peroxisome proliferation.[15]

In conclusion, our data provide evidence of the involvement of 5-hmC in the modulation of NAFLD phenotype by regulating liver mitochondrial biogenesis and the transcriptional activity of the co-activator *PPARGC1A*. In addition, our findings revealed a putative role of *TET1*-p.Ile1123Met-mediated regulation of hepatocyte apoptosis, suggesting the possibility of an ''epigenetic'' regulation of programmed liver-cell death. Using sequencing and replicated data, we also identified signatures of *TET2*-p.Ile1762Val-mediated regulation of liver *PPARGC1A* expression.

Taken together, our findings might contribute as a proof-of-concept study to the understanding of the role of DNA-hydroxymethylation and TET proteins in the molecular tissue-specific quantitative phenotypes associated with NAFLD pathogenesis and disease severity. To our knowledge, this is the first report of the influence of liver 5-hmC and *TET*-mediated

genetic susceptibility of nonmalignant complex diseases. Our results suggest the importance of early intervention once NAFLD is suspected/detected, as epigenetic modifications are potentially reversible and the altered ''liver epigenome'' can be reversed.[13,15] Emerging hypotheses remain to be explained by the use of novel technologies, including high-resolution mapping of 5-hmC regions in the mitochondrial genome and sequencing of additional candidate genes that regulate the liver methylome.

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