Impaired hepatic lipid synthesis from polyunsaturated fatty acids in TM6SF2 E167K variant carriers with NAFLD

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Background: Carriers of the transmembrane 6 superfamily member 2 E167K gene variant (TM6SF2\(^{E167K}\)) have decreased expression of the TM6SF2 gene and increased risk of NAFLD and NASH. Unlike common 'obese/metabolic' NAFLD, these subjects lack hypertriglyceridaemia and have lower risk of cardiovascular disease. In animals, phosphatidycholine (PC) deficiency results in a similar phenotype. PCs surround the core of VLDL consisting of triglycerides (TGs) and cholesteryl-esters (CEs). We determined the effect of the TM6SF2 E167K on these lipids in the human liver and serum and on hepatic gene expression and studied the effect of TM6SF2 knockdown on hepatocyte handling of these lipids.

Methods: Liver biopsies were taken from subjects characterized with respect to the TM6SF2 genotype, serum and liver lipid, gene expression and histology. In vitro, after TM6SF2 knockdown in HuH-7 cells, we compared incorporation of different fatty acids into TGs, CEs, and PCs.

Results: The TM6SF2\(^{E167K/KK}\) and TM6SF2\(^{EE}\) groups had similar age, gender, BMI and HOMA-IR. Liver TGs and CEs were higher and liver PCs lower in the TM6SF2\(^{E167K/KK}\) than the TM6SF2\(^{EE}\) group (p <0.05). Polyunsaturated fatty acids (PUFA) were deficient in liver and serum TGs and liver PCs but hepatic free fatty acids were relatively enriched in PUFA (p <0.05). Incorporation of PUFA into TGs and PCs in TM6SF2 knockdown hepatocytes was decreased (p <0.05). Hepatic expression of TM6SF2 was decreased in variant carriers, and was co-expressed with genes regulated by PUFAs.

Conclusions: Hepatic lipid synthesis from PUFAs is impaired and could contribute to deficiency in PCs and increased intrahepatic TG in TM6SF2 E167K variant carriers.

Introduction

Common non-alcoholic fatty liver disease (NAFLD) is associated with features of the metabolic syndrome, such as hypertriglyceridaemia, and increased risk of cardiovascular disease (CVD),\(^1\) In 2014, a non-synonymous adenine-to-guanine substitution (rs58542926) replacing glutamate at residue 167 with lysine (E167K) in the transmembrane 6 superfamily member 2 (TM6SF2) protein was shown to increase liver fat content\(^2,3\) and the risk of liver fibrosis.\(^4\) In these and several subsequent studies, variant allele carriers (TM6SF2\(^{E167K}\)) were found to be neither more obese nor more insulin-resistant than non-carriers (TM6SF2\(^{EE}\)).\(^5-12\) In contrast to most cases with 'obese/metabolic' NAFLD, TM6SF2 variant allele carriers have normal\(^6,10,11\) or decreased\(^2,8-10,12\) plasma TG concentrations and a reduced risk of CVD.\(^12,13\)

The exact function of the TM6SF2 variant is unknown. In hepatocytes, TM6SF2 minor allele carriage is associated with decreased TM6SF2 protein expression.\(^3\) TM6SF2 siRNA inhibition in hepatocytes increases cellular TG concentrations and reduces TG secretion, while overexpression of TM6SF2 has the opposite effect.\(^1\) In mice, hepatic knockdown of TM6SF2 increases liver triglycerides (TG) and cholestearyl esters (CE), the main constituents of the hydrophobic core of very low-density lipoprotein (VLDL) particles.\(^2\)
Research Article

Hepatic steatosis, reduced hepatic TG secretion, and protection from CVD characterize animals with deletion of genes that are involved in phosphatidylcholine (PC) synthesis such as CTP: phosphocholine cytidylyltransferase alpha (CTPα) and phosphatidylethanolamine N-methyltransferase (PEMT). A similar phenotype also results from deletion of lysophosphatidylcholine acyltransferase 3 (LPCAT3), which decreases hepatic concentrations of polyunsaturated PCs. PCs are the only phospholipids required for assembly of VLDL particles. PC deficiency increases intrahepatic degradation of VLDL particles and thereby reduces their secretion. Dietary restriction of choline, a precursor of PC, increases liver fat in humans. Consumption of a methionine-choline-deficient diet, a widely used in vivo experimental model for NAFLD and NASH, reduces hepatic PC synthesis and plasma TGs and increases liver TGs without inducing insulin resistance. In humans, a polymorphism in PEMT, which reduces PC synthesis, may be more frequent in participants with NAFLD and in participants with non-alcoholic steatohepatitis (NASH) than in those without, and characterizes participants who develop NAFLD on a choline-depleted diet. Since these changes resemble those of carriers of the TM6SF2 E167K gene variant, we hypothesized that reduced PC synthesis might characterize carriers of the E167K variant.

In the present study, we profiled hepatic gene expression and measured concentrations of TGs, CEs, PCs and free fatty acids (FFA) in human liver biopsy samples from carriers (TM6SF2EK/EE) and non-carriers (TM6SF2KK) of the TM6SF2 E167K variant. Since the in vivo results seemed to support our hypothesis, we directly measured incorporation of saturated (16:0, palmitic acid), monounsaturated (18:1, oleic acid), and polyunsaturated fatty acids (20:4, arachidonic acid) into TG, CE, and PC pools in TM6SF2 knockdown HuH-7 cells. In addition, we measured circulating concentrations and composition of TGs, CEs and PCs in carriers and non-carriers of the gene variant.

Materials and methods

Study participants

Ninety participants were recruited from a cohort of patients undergoing laparoscopic bariatric surgery. Following a phone interview and a separate clinical study visit (vide infra), participants were eligible if they met the following inclusion criteria:

a. Age 18 to 75 years.
b. No known acute or chronic disease except for features of the metabolic syndrome based on medical history, physical examination and standard laboratory tests (complete blood count, serum creatinine, electrolyte concentrations).
c. Non-diabetic based on 2 h plasma glucose concentrations (<11 mmol/l) during a 75 g oral glucose tolerance test.
d. Alcohol consumption less than 20 g per day in women and less than 30 g per day in men.
e. No clinical or biochemical evidence of other liver disease, or clinical signs or symptoms of inborn errors of metabolism.
f. No use of drugs or toxins influencing liver steatosis.

Elevated liver enzymes (alanine aminotransferase (ALT) and aspartate aminotransferase (AST)) were not exclusion criteria. Participants with diabetes were excluded from the present study, as we wished to study the impact of the TM6SF2 genotype at rs58542926 rather than that of insulin resistance/diabetes and anti-diabetic drugs on the human liver lipidome. The effect of the latter was reported earlier in a larger (n = 125) group of participants, which included patients with diabetes. The ethics committee of the Hospital District of Helsinki and Uusimaa approved the study, which was conducted in accordance with the Declaration of Helsinki. Each participant provided written informed consent after the nature and potential risks of the study had been fully explained.

Metabolic study

One week prior to surgery, all participants were invited to a clinical visit for metabolic characterization after an overnight fast. Anthropometric measurements (body weight, height and waist circumference) were taken, an intravenous cannula inserted in an antecubital vein and blood collected for measurement of HbA1c, serum insulin and adiponectin, plasma glucose, LDL- and HDL-cholesterol, triglyceride, AST, ALT, ALP, GGT and albumin concentrations and for genotyping of PNPLA3 rs738409 and TM6SF2 rs58542926 as previously described. The participants underwent an oral glucose (75 g) tolerance test (OGTT). HOMA-IR and Matsuda insulin sensitivity index were used as surrogates for insulin resistance. Body weight of the participants did not differ between the time of the metabolic study and surgery (128.9 ± 2.3 and 128.5 ± 2.3 kg; non-significant [NS]). The participants were divided into groups based on their TM6SF2 rs58542926 genotype (E167K variant allele carriers, TM6SF2EK/EK, n = 10 and non-carriers, TM6SF2KK, n = 80).

Liver biopsies and liver histochemistry

Routine wedge biopsies of the liver were taken immediately at the beginning of the surgery. Part of the biopsy was snap-frozen in liquid nitrogen for subsequent analysis of molecular lipids and gene expression; the other part was sent to an experienced liver pathologist (J.A.) for blinded analysis of liver histology according to the criteria proposed by Brunt et al. Liver fat was quantified as the percentage of hepatocytes with macrovesicular steatosis.

Hepatic lipidomic and free fatty acid analysis

Hepatic lipidomic analyses of TGs, CEs and PCs were performed using a Q-TOF Premier (Waters, Milford, MA) quadrupole time-of-flight mass spectrometer combined with an Acquity Ultra Performance liquid chromatograph (LC) (Waters, Milford, MA). Liquid chromatography methods are described in the Supplementary material. Hepatic FFAs were analysed using an Agilent 6890 gas chromatograph equipped with a split/splitless injector (Agilent Technologies, Santa Clara, CA), cryogenic dual-stage modulator and time-of-flight mass spectrometer (Leco Corp., St. Joseph, MI, USA) as described in detail in Supplementary material. All analyses were blinded.

Hepatic RNA sequencing

Since the results (vide infra) suggested that TM6SF2 might be involved in synthesis of polyunsaturated lipids, we examined hepatic gene expression using RNA sequencing. For this, liver samples were available from 69 of the original cohort. An additional 25 participants were recruited using the same criteria as the original cohort. The characteristics of these participants (n = 94) are shown in Table S2. The samples were prepared using Illumina TruSeq RNA Sample Preparation Kit (Illumina, San Diego, CA) and sequencing was performed using a paired-end 101 base pair protocol on HiSeq2000 platform (Illumina, San Diego, CA). The methods for RNA sequencing, data processing and pathway analysis are described in detail in the Supplementary material.

Serum lipidomic analysis

Serum lipidomic analyses of TGs, CEs and PCs were analysed using an ultra-high-performance liquid chromatography quadrupole time-of-flight mass spectrometer (UHPLC-Q-TOF-MS). The UHPLC was a 1290 Infinity system (Agilent Technologies, Santa Clara, CA) and the mass spectrometer a 6550 iFunnel Q-TOF (Agilent Technologies, Santa Clara, CA). Details of the sample preparations and data preprocessing steps are given in Supplementary material.

In vitro experiments

Stably transduced and transiently silenced HuH-7 human hepatoma derived cells were used as in vitro hepatocyte models. The former was established by transducing HuH-7 cells with lentiviral particles expressing shRNA against TM6SF2
The Kolmogorov-Smirnov test was used to test the normality of continuous variables. The independent two-sample Student’s t test and Mann-Whitney U test were used to compare normally and non-normally distributed data, respectively. Normally distributed data were reported in means ± standard error of means (SEM) while non-normally distributed data were reported as medians followed by interquartile ranges. Pearson’s χ² test was used to evaluate if the distribution of categorical variables differed between the groups. Pearson’s correlation coefficients were calculated as a measure of statistical dependence between two variables after log-transformation if necessary. Statistical analyses were performed by using R 3.1.1 (http://www.r-project.org/), IBM SPSS Statistics 22.0.0.0 version (IBM, Armonk, NY), and GraphPad Prism 6.0f for Mac OS X (GraphPad Software, La Jolla, CA). A two-sided p value of less than 0.05 indicated statistical significance.

The median and, after log2-transformation, the mean concentrations of all lipids were compared between groups based on TM6SF2 genotype. Benjamini-Hochberg method was used for multiple hypotheses testing. 20 Differences in concentrations of TGs were illustrated by a heat map, where the color intensity of each cell represents the log2-transformed ratio of mean values of an individual TG in the TM6SF2EE/KK group divided by the mean values in the TM6SF2EK group. Fold-change of log2-transformed ratio of mean concentrations of lipids between the groups was visualized with respect to fatty acyl chain length and saturation.

For further details regarding the materials used, please refer to the CTAT table.

Table 1. Clinical characteristics of the study participants according to the TM6SF2 genotype at rs58542926.

<table>
<thead>
<tr>
<th>Total</th>
<th>TM6SF2EE (n = 80)</th>
<th>TM6SF2EK/KK (n = 10)</th>
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<tr>
<td>Age (years)</td>
<td>45.2 ± 0.9</td>
<td>49.1 ± 2.8</td>
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<tr>
<td>Gender (% women)</td>
<td>71.3</td>
<td>70.0</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>45.4 ± 0.7</td>
<td>45.6 ± 1.7</td>
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<tr>
<td>Waist circumference (cm)</td>
<td>128.3 (120.0–140.0)</td>
<td>127.3 (117.4–135.4)</td>
</tr>
<tr>
<td>Liver fat (%)</td>
<td>27.5 ± 9.5*</td>
<td></td>
</tr>
<tr>
<td>Nocirealnflammatory grade (0/1/2/3)</td>
<td>67/13/0/0</td>
<td>8/2/0/0</td>
</tr>
<tr>
<td>Fibrosis stage (0/1/2/3/4)</td>
<td>55/23/2/0/0</td>
<td>4/5/10/0</td>
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<tr>
<td>Fibrosis stage &gt; 0 (%)</td>
<td>31</td>
<td>60 (p = 0.09)</td>
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<tr>
<td>fS-insulin (mU/L)</td>
<td>12.6 (6.9–18.8)</td>
<td>12.8 (7.7–17.7)</td>
</tr>
<tr>
<td>fP-glucose (mmol/L)</td>
<td>5.6 ± 0.1</td>
<td>5.7 ± 0.3</td>
</tr>
<tr>
<td>HbA1c (%)</td>
<td>5.7 (5.5–6.0)</td>
<td>5.7 (5.5–6.1)</td>
</tr>
<tr>
<td>HbA1c (mmol/mol)</td>
<td>39 (37–42)</td>
<td>39 (37–43)</td>
</tr>
<tr>
<td>HOME-IR</td>
<td>3.4 ± 0.2</td>
<td>3.6 ± 0.7</td>
</tr>
<tr>
<td>Matsuda index*1</td>
<td>55.4 (36.0–104.9)</td>
<td>56.9 (42.2–74.3)</td>
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<tr>
<td>fS-adiponectin (µg/ml)</td>
<td>8.5 ± 0.5</td>
<td>10.1 ± 1.3</td>
</tr>
<tr>
<td>fP-total cholesterol (mmol/L)</td>
<td>4.3 ± 0.1</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>fP-triglycerides (mmol/L)</td>
<td>1.24 (0.91–1.69)</td>
<td>1.34 (0.97–1.60)</td>
</tr>
<tr>
<td>fP-HDL cholesterol (mmol/L)</td>
<td>1.13 (0.96–1.37)</td>
<td>1.09 (0.96–1.55)</td>
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<tr>
<td>fP-LDL cholesterol (mmol/L)</td>
<td>2.6 ± 0.1</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>P-AST (IU/L)</td>
<td>30 (25–37)</td>
<td>34 (30–41)</td>
</tr>
<tr>
<td>P-ALT (IU/L)</td>
<td>32 (24–45)</td>
<td>42 (28–58)</td>
</tr>
<tr>
<td>P-ALP (IU/L)</td>
<td>64 ± 2</td>
<td>70 ± 5</td>
</tr>
<tr>
<td>P-GGT (IU/L)</td>
<td>28 (21–45)</td>
<td>50 (26–66)</td>
</tr>
<tr>
<td>P-albumin (g/L)</td>
<td>39.2 ± 0.3</td>
<td>37.9 ± 1.0</td>
</tr>
<tr>
<td>B-platelets (x 10^3/µL)</td>
<td>252 ± 6</td>
<td>276 ± 35</td>
</tr>
<tr>
<td>PNPLA3 (n, CC/CG/GG)</td>
<td>41/35/4</td>
<td>6/3/1</td>
</tr>
<tr>
<td>TM6SF2 (n, CT/TT)</td>
<td>80/0/0</td>
<td>0/0/1**</td>
</tr>
</tbody>
</table>

Data are in n, means ± SEM or median (25th–75th percentile), and statistical tests are Student’s t test, Mann-Whitney U test and Pearson’s χ²-test, as appropriate. *p < 0.05.
**p < 0.001.
*1 Homeostasis model assessment of insulin resistance was calculated by formula: fS-insulin x fP-glucose/22.5 according to Matthews et al. 21
*1 Matsuda insulin sensitivity index was calculated from insulin and glucose concentrations measured at 0, 30 and 120 min during the oral glucose tolerance test as proposed by DeFronzo and Matsuda. 22
The concentration of total liver CEs was 20% higher in the TM6SF2<sup>EE/KK</sup> than the TM6SF2<sup>EE</sup> group (p < 0.05) (Fig. 4). Among individual CE species, the concentration of CE(16:0) was significantly higher in the TM6SF2<sup>EE/KK</sup> group than the TM6SF2<sup>EE</sup> group (p < 0.05), while those of CE(16:1), CE(18:1) and CE(18:2) tended to increase (p = 0.07, p = 0.06, and p = 0.05, Fig. 4). In TM6SF2 knockdown HuH-7 cells, incorporation of palmitic acid (16:0) into CE was significantly (+149%, p < 0.05) and that of oleic acid (18:1) almost significantly (+76%, p = 0.06, Fig. 3E) increased. Transient silencing of TM6SF2 in HuH-7 cells induced similar changes in fatty acid incorporation into CEs (Fig. S2C).

### Hepatic PCs

In the human liver samples, total PCs were significantly lower in the TM6SF2<sup>EE/KK</sup> than the TM6SF2<sup>EE</sup> group (−11%, p < 0.05; Fig. 4). The fold-change of PCs between the groups was significantly inversely correlated with the number of double bonds (r = −0.40, p < 0.001) but not with the number of carbons in PCs. Thus, polyunsaturated PCs were responsible for the decrease in total PCs (Fig. 4). To determine whether the decrease in polyunsaturated PCs was secondary to an increase in liver TG, we plotted liver TGs against individual polyunsaturated PC concentrations. As shown in Fig. S3, for any given liver TG concentration, those of polyunsaturated PCs were significantly lower in the TM6SF2<sup>EE/KK</sup> than the TM6SF2<sup>EE</sup> group.

In TM6SF2 knockdown HuH-7 cells, the relative incorporation of arachidonic acid to PC was significantly lower than in control cells (−32%, p < 0.05, Fig. 3F), while incorporations of palmitic (+236%, p < 0.001) and oleic (+65%, p < 0.05) acids were increased (Fig. 3D). Transient silencing of TM6SF2 expression in HuH-7 cells induced similar changes in fatty acid incorporation into PCs (Fig. S2B).

### Hepatic FFA

The concentration of total hepatic FFA was significantly lower in the TM6SF2<sup>EE/KK</sup> (700 [595–822] nmol/g) than the TM6SF2<sup>EE</sup> group (904 [755–1,098] nmol/g, p < 0.01). Among the individual FFA, concentrations of palmitic (16:0; 286 [254–346] nmol/g) vs. 383 [307–456] nmol/g, p < 0.01), stearic (18:0; 131 [125–188] vs. 195 [160–231] nmol/g, p < 0.01), oleic (18:1; 140 [131–168] vs. 191 [141–247] nmol/g, p < 0.05) and linoleic (18:2; 67 [50–81] vs. 84 [67–102] nmol/g, p < 0.05) acids were significantly lower in the TM6SF2<sup>EE/KK</sup> compared to the TM6SF2<sup>EE</sup> group (Fig. 4). The relative proportion of arachidonic acid (20:4) in total FFA was significantly higher (+15%, p < 0.05) in the TM6SF2<sup>EE/KK</sup> compared to the TM6SF2<sup>EE</sup> group (Fig. 4).
Fig. 3. In vitro experiments. A) TM6SF2 mRNA expression in control shRNA (shNT) and TM6SF2 shRNA (shTM6SF2) expressing HuH-7 cells. The experiment was run twice in triplicates. B) Staining of lipid droplets by BODIPY® 493/503 in shNT and shTM6SF2 expressing HuH-7 cells and C) the quantification of lipid droplet area per cell. The data represent the average of 150 cells from each set. The relative incorporation of \(^{[3]H}\)-palmitic acid, \(^{[3]H}\)-oleic acid and \(^{3}H\)-arachidonic acid into triglycerides (D), cholesteryl esters (E) and phosphatidylcholines (F) expressed in percentage relative to control (n = 5). Data are shown as mean ± SD; Student's test; *p < 0.05, **p < 0.01, ***p < 0.001.

Serum TGs, PCs and CEs

In the serum, the fold-change of TGs in the TM6SF2\(^{E167K}\) group tended to inversely correlate with the number of double bonds (p = 0.07) and number of carbons (p = 0.07) in TGs (Fig. 5). The intercepts of the fold-change regression lines between the groups were highly significantly, lower than 0 in serum TGs and PCs according to number of double bonds (p < 0.0001 for both TGs and PCs) and carbons (p < 0.0001 for both), but not in serum CEs (Fig. 5).

Hepatic gene expression

TM6SF2 mRNA expression was significantly downregulated in variant allele carriers (number of rs58542926 minor (T) alleles vs. TM6SF2 expression, \(\beta = -0.41 \pm 0.11, p < 0.001\). Fig. S4). In pathway analyses, three pathways related to lipids, i.e. 'metabolism of lipids and lipoproteins', 'peroxisomal lipid metabolism' and 'triglyceride synthesis', were enriched with genes significantly correlated with TM6SF2 (Fig. 6; Table S3). Among individual genes which were positively co-expressed with TM6SF2 (and therefore decreased in TM6SF2 E167K carriers) were those associated with fatty acid (fatty acid synthase [FASN], acetyl-CoA carboxylase beta [ACACB]) and triglyceride (diacylglycerol acyltransferase [DGAT1], DGAT2) synthesis, and VLDL metabolism (apolipoprotein C-III [APOC3]), while those which were inversely co-expressed with TM6SF2 included genes related to fatty acid oxidation (carnitine palmitoyltransferase 1 [CPT1]), peroxisome proliferator-activator receptors alpha and gamma (PPARA, PPARG) and eicosanoid synthesis (arachidonate 5-lipoxygenase [ALOX5]) (Fig. 6).

Discussion

To the best of our knowledge, this is, the first study to compare human hepatic lipid profiles between carriers and non-carriers of the TM6SF2 E167K gene variant. Variant allele carriers had significantly higher hepatic TGs and CEs but lower total PCs due to a decrease in polyunsaturated PCs. Polysaturated fatty acids (PUFAs) were also deficient in serum and liver TGs but relatively enriched in liver FFA (Fig. 7). Consistent with this in vivo finding, using stably transduced and transiently silenced HuH-7 cells as
The number of ACS enzymes has rapidly increased with the expression of TM6SF2. Bold italics denote genes regulated by polyunsaturated fatty acids.31,33-35

in vitro hepatocyte models, TM6SF2 knockdown led to reduced incorporation of PUFAs into PCs and TGs. In the human liver, TM6SF2 was downregulated in variant allele carriers. Thus, down-regulation of TM6SF2 increases liver TG and CE and decreases PC content by impairing lipid synthesis from PUFAs.

To examine the effect of the TM6SF2 E167K variant on human hepatic lipid content and composition, we divided the participants based on TM6SF2 genotype (TM6SF2E167K vs. TM6SF2KK). Carriers of this gene variant had 2-fold higher liver fat content but the groups did not differ with respect to HOMA-IR or insulin or glucose concentrations during the OGTT or obesity. PNPLA3 genotype, which influences hepatic lipid composition, was also similar between the groups. Lack of features of insulin resistance between carriers and non-carriers of the TM6SF2 allele is similar to the finding of Kozlitina et al. in three independent cohorts.2 In keeping with several previous studies involving 300,361 and 6912 participants, there was no difference in fasting plasma triglyceride concentrations between the TM6SF2 genotype groups. However, in larger studies including 73034,1,20112 and 4,5872 participants, the variant allele has been associated with decreased circulating triglycerides. In the present study, variant allele carriers displayed deficiency of TGs and PCs in the circulation as compared to non-carriers in serum lipids analysis (Fig. 5). Deficiency of TGs and PCs in serum in the face of increased liver TG suggests defective hepatic lipid export, in line with previous data.2,8-10,12

In the liver of TM6SF2 E167K variant carriers compared to non-carriers (Fig. 2, Fig. 4; Fig. S1) and in vitro in hepatocytes (Fig. 3D, F), PUFAs in both PCs and TGs were decreased while the proportion of polyunsaturated arachidonic acid in total liver FFA was increased (Fig. 4). These results imply that the TM6SF2 E167K variant may regulate channeling of PUFAs into PC and TG synthesis. The first step in the incorporation of free PUFAs into these lipids is activation into a fatty acyl-CoA by an acyl-CoA synthetase (ACS) enzyme.32 The number of ACS enzymes has rapidly increased and includes at least 26 isoforms.34 These enzymes vary with respect to their substrate preference and subcellular localisation, and channel distinct fatty acids into different metabolic pathways.13,34 For example, knockdown of acyl-CoA synthetase long-chain family member 3 (ACSL3), which is expressed in the liver and intestine and localised in the endoplasmic reticulum similarly to TM6SF2, decreases incorporation of unsaturated fatty acids into PC, causes PC deficiency, and inhibits secretion of VLDL in HuH-7 cells.35

Regarding the mechanisms by which PC deficiency and excess polyunsaturated FFA interfere with VLDL metabolism, assembly, secretion and degradation of VLDL needs to be considered. The assembly of VLDL has two major steps.36 First, a nascent VLDL particle is formed in the ER, where it undergoes maturation to become a relatively lipid-poor small VLDL1 particle.36 This small particle is translocated to the Golgi complex and may be secreted as such, or undergoes a second lipidation step in which more TGs and CEs are added to the particle to form a highly-lipidated large VLDL2 particle.36

**Metabolism of lipids and lipoproteins**

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<th>Gene</th>
<th>Function</th>
<th>Regulation</th>
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<td>APOC3, ECHS1, SLC25A1, FASN, APOE, ACOX3, DGAT1, DGAT2, APOA2, HADH, SLC01B3, SLC25A17, EC11, ACOX2, LPIN3, NEU4, MED11, ARSA, HSD11B1, GP1, AKR1B1, BAAT, PHYH, ACADS, GPM, SLC27A5, AGPAT3, SCARB1, NPC1L1, CYP17A1, CRAT, CYP8B1, MVK, ACACB, ABCC3, FADS, CYP46A1, LSS, GPD2, GPHC, FAR1, CYP7B1, PPARA, LBR, ARNTL, ASAH1, SGP1, CPT1A, A2M, PPARG, OXCT1, GLIPR1, CLOCK, ALOX3, LRP2, SPTLC2, AGPS</td>
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**Triglyceride biosynthesis**

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**Peroxisomal lipid metabolism**

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<td>ACOX3, SLC25A17, ACOX2, PHYH, CRAT, FAR1, AGPS</td>
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Fig. 6. Hepatic lipid-related gene expression pathways enriched with genes co-expressing with TM6SF2. Names of the pathways are in bold and names of the genes in italics. Blue color denotes genes correlating positively (i.e. decreasing in TM6SF2 E167K carriers) and red color those correlating negatively with the expression of TM6SF2. Bold italics denote genes regulated by polyunsaturated fatty acids.31,33-35

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In *TM6SF2* knockout mice, large VLDL particles are deficient in the circulation in the face of an unchanged or increased total number of particles secreted. This was suggested to reflect a defect during the second lipidation step. Consistent with these data in mice, in humans, large VLDL particles are markedly deficient in the circulation in *TM6SF2* E167K variant allele carriers compared to non-carriers. This may be caused by PC deficiency or excess polyunsaturated FFA. For example, in isolated mouse hepatocytes, reduced PC synthesis due to knockout of *PEMT* increases degradation and decreases secretion of particularly the highly-lipidated VLDL particles. Polyunsaturated FFA increase VLDL degradation by a similar mechanism. Thus, PC deficiency and the relative increase in polyunsaturated FFA in *TM6SF2* variant carriers might lead to accumulation of TGs and CE via degradation of highly-lipidated VLDL, in keeping with the conclusion of Hobbs and coworkers.

Hepatic expression of *TM6SF2* mRNA was decreased in E167K variant carriers (Fig. S4). Three lipid-related pathways were enriched with genes co-expressing with *TM6SF2* (Fig. 6). Among individual genes, expression of those related to lipogenesis and lipid export (e.g. FASN, ACC1, DGAT2, DGAT1 and APOC3) was decreased, while expression of genes related to peroxisome proliferator-activated receptors, mitochondrial fatty acid oxidation, and eicosanoid synthesis (e.g. PPARE, PPARG, CPT1, ALOX5) was increased in the variant carriers (Fig. 6). Decreased expression of DGAT1 and DGAT2 in variant carriers is in line with previous *in vitro* data. Interestingly, virtually identical changes in these genes are induced by PUFAs, in part via transcriptional regulation by peroxisome proliferator-activated receptors (Fig. 6). These findings are consistent with the *in vivo* and *in vitro* data suggesting impaired hepatic incorporation of PUFAs to TGs, CEs and PCs, increased relative concentrations of arachidonic acid in hepatic FFA, and deficiency of TGs and PCs in serum in *TM6SF2* E167K variant carriers.

Although we observed PC deficiency both in the liver and in serum in humans carrying the *TM6SF2* E167K variant compared to non-carriers, no changes in hepatic PC concentrations were observed in *TM6SF2* knockout mice. This could be due to species difference. The main finding of the present study, i.e. impaired hepatic lipid synthesis from PUFAs in *TM6SF2* E167K variant carriers, however, is entirely compatible with data in *TM6SF2* knockout mice displaying reduced percentage of 20:4 and 22:6 in total hepatic lipids.

Even though the sample size in the present study was large considering the difficulty in obtaining human liver samples, the number of variant allele carriers was low given the variant allele frequency of 7%. The observed differences may thus underestimate true differences between carriers and non-carriers of the *TM6SF2* E167K gene variant. We had no detailed dietary records to detect differences between carriers and non-carriers of the *TM6SF2* E167K gene variant. The percentage of hepatic free 20:4 fatty acid (FA) is increased in vivo. First step in synthesis of cholesteryl esters (CE), triglycerides (TG), and phosphatidylylcholines (PC) is activation of free fatty acids into acyl-coenzyme A (CoA). These acyl-CoAs are esterified with cholesterol to form CEs. The in vitro incorporation of 20:4 into CEs is decreased, and concentrations of serum polyunsaturated CE are decreased in vivo. Acyl-CoAs are also utilized in *de novo* synthesis (via synthesis of lysophosphatidic acid, phosphatidic acid and diacylglycerol) of TGs and PCs. Incorporation of 20:4 into TGs and PCs is decreased in vivo, and hepatic concentrations of polyunsaturated TGs and PCs are decreased in vivo. Hepatic gene expression in vivo is characterized by changes in the expression of genes regulated by free PUFAs. In summary, these *in vivo* and *in vitro* findings suggest that hepatic lipid synthesis from PUFAs is impaired in *TM6SF2* E167K variant carriers.
and apoptosis,66 and stellate cell collagen expression in vitro,47 while arachidonic acid deficiency has opposite effects.10 Arachidonic acid can be metabolized into proinflammatory eicosanoids,33 which circulating concentrations are increased in participants with NASH.9,56 Increased liver fat content per se may increase the risk of NASH, as evidenced by recent prospective liver biopsy data.31

In conclusion, hepatic synthesis of polyunsaturated fatty acid-containing lipids is impaired in TM6SF2 E167K gene variant carriers and leads to deficiency of polyunsaturated PCs and excess polyunsaturated FFA in the human liver. These changes, based on abundant experimental data, could impair VLDL lipidation via increased degradation, and explain the phenotype characterizing TM6SF2 E167K carriers i.e. hepatic steatosis, lack of circulating hypertriglyceridemia and an increased risk of NASH.

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Conflict of interest

The authors who have taken part in this study declared that they do not have anything to disclose regarding funding or conflict of interest with respect to this manuscript.

Please refer to the accompanying ICJME disclosure forms for further details.

Authors’ contributions

PL – study concept and design; acquisition of data; analysis and interpretation of data; drafting of the manuscript; critical revision of the manuscript for important intellectual content; statistical analysis. YZ, OPD, TT, PV – bioinformatics and statistical analyses; interpretation of data; critical revision of the manuscript for important intellectual content. PANH, VO – further details.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhep.2017.02.014.

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Author names in bold designate shared co-first authorship


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