Non-Linear Formation of EtG and FAEEs after Controlled Administration of Low to Moderate Doses of Ethanol

Clara Pérez-Mañana1,2,†, Magí Farré2,3,*,†, Antoni Pastor1,2,4, Francina Fonseca2,5, Marta Torrens2,5, Esther Menoyo1, Mitona Pujadas1,4, Silvia Frias1, Klaus Langohr1,6, and Rafael de la Torre1,4,7

1Integrative Pharmacology and Systems Neurosciences Research Group, Neurosciences Research Program, IMIM (Hospital del Mar Medical Research Institute), Doctor Aiguader 88, 08003 Barcelona, Spain, 2Autonomous University of Barcelona (UAB), 08193 Cerdanyola del Vallès, Spain, 3Department of Clinical Pharmacology, Hospital Universitari Germans Trias i Pujol-IGTP, Carretera de Canyet, s/n, 08916 Badalona, Spain, 4CIBER de Fisiopatología de la Obesidad y la Nutrición (CIBERObn), Instituto de Salud Carlos III, Monforte de Lemos 3-5, 28029 Madrid, Spain, 5Drug Addiction Unit, Institute of Neuropsychiatry and Addictions (INAD), IMIM, Parc de Salut Mar, Doctor Aiguader 88, 08003 Barcelona, Spain, 6Department of Statistics and Operations Research, Universitat Politècnica de Catalunya (UPC)/BarcelonaTech, Jordi Girona 1-3, 08034 Barcelona, Spain, and 7Pompeu Fabra University (CEXS-UPF), Plaça de la Mercè 10-12, 08002 Barcelona, Spain

*Corresponding author: Department of Clinical Pharmacology, Hospital Universitari Germans Trias i Pujol (IGTP), Carretera de Canyet, s/n, Badalona 08916, Spain. Tel: +34-93-4978865; Fax: +34-93-4651200; E-mail: mfarre.germanstrias@gencat.cat

†Authorship credit should be equally distributed among the authors independently of the order.

Received 6 February 2017; Revised 4 April 2017; Accepted 9 May 2017

Abstract

Aims: Ethyl glucuronide (EtG) and fatty acid ethyl esters (FAEEs) are non-oxidative metabolites of alcohol that can be detected in conventional and non-conventional biological matrices for longer periods than alcohol. The aim was to describe the time courses of both biomarkers after ingestion of acute low–moderate doses of ethanol.

Methods: The study design was double-blind, randomized, crossover and controlled with placebo. Participants were distributed in three different cohorts: (a) Cohort-1: two doses of 18 and 30 g of ethanol and placebo were administered to 12 subjects; (b) Cohort-2: two doses of 6 and 12 g of ethanol and placebo were administered to six subjects and (c) Cohort-3: two doses of 24 and 42 g of ethanol and placebo were administered to six subjects. Each participant received two doses of ethanol and placebo. Plasma concentrations (0–6 h) of ethanol and specific FAEEs (palmitic, stearic, linoleic and oleic acid ethyl esters) and urinary concentrations of EtG (0–24 h) were measured.

Results: A dose-dependent increase in blood ethanol concentrations was observed. EtG excretion and FAEEs plasmatic concentrations showed a disproportionate increase with the ethanol dose suggesting non-linearity. Area under the curve (AUC0–6 h) of ethanol concentrations showed a linear trend with non-oxidative metabolites’ concentrations.

Conclusion: The formation rate of ethanol non-oxidative biomarkers does not follow a linear trend, explained mainly by a disproportionate increase in AUC0–6 h of ethanol concentrations in relation...
to dose. This observation should be taken into account when interpreting results in biological matrices in clinical and forensic settings.

**Short summary:** A double-blind, randomized, crossover and controlled study was conducted administering ethanol (6–42 g). Ethyl glucuronide (EtG) excretion and fatty acid ethyl esters (FAEEs) plasmatic concentrations showed a disproportionate increase with the ethanol dose suggesting non-linearity. This observation should be taken into account when interpreting biomarker concentrations in clinical settings.

**INTRODUCTION**

Alcohol is the most worldwide consumed legal drug and alcohol use disorders are common in modern societies (WHO, 2014). Biomarkers of alcohol consumption are used to prevent health and social problems related with alcohol, allowing the identification of subjects at a higher risk of alcohol use disorders or withdrawal and to assess the efficacy of treatments for alcohol dependence (Botaille et al., 2003; Kip et al., 2008; Dahl et al., 2011).

The interest in non-oxidative metabolites of alcohol has grown in the last years due to the lack of accuracy or inadequacy for purpose of previously developed biomarkers and the possibility to detect them in conventional specimens and alternative biological matrices (Cabarcos et al., 2015).

Ethanol is converted to acetaldehyde by hepatic oxidative metabolism (95–98%) in a reaction regulated by class I isozymes of alcohol dehydrogenase (ADH) and highly inducible microsomal CYP2E1. In turn acetaldehyde is converted in acetic acid (acetate) by acetaldehyde dehydrogenase. Only a small fraction of ethanol (2–5%) is excreted unchanged in urine, sweat or exhaled air, or follows non-oxidative metabolism, leading to minor metabolites such as ethyl glucuronide (EtG), ethyl sulfate, ethyl phosphate, phosphatidylethanol and fatty acid ethyl esters (FAEEs).

Blood, urine or breath ethanol concentrations are useless biomarkers of abstinence because ethanol is cleared from the body at a rate of 0.1–0.25 g l$^{-1}$ h$^{-1}$ and becomes undetectable in blood in a few hours (Borucki et al., 2005; Jatlow and O’Malley, 2010). Clearance in heavy drinkers is still faster due to CYP2E1 induction (Jones, 2008).

Non-oxidative metabolites have longer biological half-lives than ethanol, accumulate in tissues after consumption and allow the detection of ethanol consumption after larger periods of abstinence. The detection window of non-oxidative metabolites may last for several hours up to some days, depending on the marker and the amount of alcohol ingested.

EtG is produced by UDP-glucuronosyltransferase (UGT), it can be detected in urine up to 80 h after ethanol ingestion (Wurst et al., 2003) and does not accumulate after repeated drinking (Sarkola et al., 2003). EtG has a similar excretion profile and can be used for confirmation of EtG tests (Jatlow and O’Malley, 2010).

In turn FAEEs are produced by esterification of fatty acids and ethanol through FAEEs synthase and acyl-CoA/ethanol O-acyl-transferase (Treboar et al., 1996). They appear in the serum bound to albumin and in the core of lipoproteins (Laposata, 1997) and are associated with alcohol organic damage (Laposata, 1999). FAEEs can be detected in blood up to 24 h after a drinking intoxication (Doyle et al., 1994), and up to 44 h in heavy drinkers (Borucki et al., 2004).

Direct ingestion of FAEEs should be considered as they have been detected in food, scotch whiskey and non-alcoholic beverages (Goss et al., 1999). Moreover, both FAEE and EtG are also formed endogenously and have been detected in ethanol abstainers and children. For FAEEs, a baseline range from natural human metabolism has been described while EtG could be produced from ethanol generated by intestinal bacteria (Borucki et al., 2005; Rosano and Lin, 2008).

Their monitoring after recent or even single consumption in law enforcement and forensic cases is common, but their application to clinical settings is still limited (Jatlow and O’Malley, 2010). EtG is the one with the most opportunities to be routinely assessed in treatment programs (high sensitivity and specificity, wide detection period, detection of low doses and availability of enzyme immunoassay commercial kits) (Wurst et al., 2003; Borucki et al., 2005). Additionally, EtG can be used in clinical trials for confirmation of self-reported alcohol abstinence (Jatlow et al., 2014).

We have identified several experimental studies assessing urine or blood EtG (Sarkola et al., 2003; Haïsset et al., 2007, 2008; Halter et al., 2008) or blood FAEEs (Doyle et al., 1994, 1996; Laposata, 1997; Schmitt et al., 1997; Soderberg et al., 1999; Dahl et al., 2002; Goll et al., 2002; Best and Laposata, 2003; Best et al., 2006) detection after administration of one dose of ethanol or a dose targeted to reach a fixed alcohol concentration. Three studies have described a dose-dependent increase in urinary EtG concentrations after administration of different doses of ethanol to the same subjects (Rosano and Lin, 2008; Haïsset et al., 2010; Jatlow et al., 2014). A non-randomized study assessed urine EtG and plasma FAEEs simultaneously recommending the use of urine EtG as marker of recent alcohol intake (Borucki et al., 2005).

However, no randomized studies assessing both biomarkers (EtG and FAEEs) in healthy subjects and covering a dose range compatible with social consumption of ethanol have been identified.

Our objective was to describe the time course of both biomarkers after ingestion of low–moderate doses of ethanol trying to avoid potential confounders by means of a randomized and placebo controlled clinical trial.

**MATERIALS AND METHODS**

**Participants**

The study was conducted in accordance with the Declaration of Helsinki, approved by the local Research Ethics Committee (Comité Étique d’Investigación Clínica Parc de Salut Mar) and registered (clinical trials.gov: NCT01788670).

Eligibility criteria required to be healthy subjects with social ethanol consumption. Exclusion criteria were daily alcohol consumption of >30 g or current or previous ethanol abuse or dependence. All subjects were informed and signed a consent form before...
the first study related procedure and were financially compensated for their participation.

Twenty-four male healthy volunteers were included. All of them were randomized and finished the study. One third of them were smokers and their average alcohol consumption was 7 g a day. The mean age, body weight and height were 25.8 years (range 20–36), 79.2 kg (range 65.4–92.2) and 181 cm (range 172–189).

Study design and procedures
Participants were distributed in three different cohorts. Design was double-blind, randomized, crossover and controlled with placebo. In Cohort-1 drinks containing 18 and 30 g of ethanol and placebo were administered to 12 subjects; in Cohort-2 drinks containing 6 and 12 g of ethanol and placebo were administered to six subjects and in Cohort-3 drinks containing 24 and 42 g of ethanol and placebo were administered to six subjects.

Recruitment and sessions took place in the Clinical Research Unit at Hospital del Mar Medical Research Institute-IMIM.

Sessions lasted 6 h with a minimum wash-out period between sessions of at least 3 days. Participants on each cohort were randomly assigned by order of recruitment to one treatment sequence using a balanced 3 × 3 Latin square design. Allocation for each participant was concealed for all the staff (beverages were prepared by personnel not involved in the experimental sessions).

Subjects were requested to abstain from ethanol ingestion and the use of other sources of ethanol (hand sanitizers, mouthwashes) 3 days before each session. Breath alcohol tests (Dräger Breathalyzer 7410 Plus, Denmark) and drugs of abuse tests in urine (Instant-View; ASD Inc, Poway, CA, USA) were conducted at baseline to confirm abstinence. Xanthine-containing foods/drinks were prohibited from the day before till 24 h after administration.

On each session day an intravenous catheter was inserted into an arm subcutaneous vein to obtain blood samples. Treatments were administered at 8:30 AM and half cheese sandwich with sunflower oil was provided 2 and 6 h after treatment administration. Additional water was given to volunteers at 2 h (300 ml) and 4 h (100 ml) in order to assure urine generation in each time interval. Participants left the unit 6 h after administration after verifying that the breath alcohol test was negative.

Treatments
Ethanol conditions were obtained by mixing ethanol pharmaceutical grade and lemonade flavored water (Fontvella Sensación sabor limón, Barcelona, Spain). Placebo contains only lemonade flavored water. The total volume of the beverages was 150 ml. All the beverages were consumed in fasting conditions, orally, in opaque recipients and in 5 min.

Blood and urine samples
Blood samples to determine ethanol and FAEEs (palmitic, stearic, oleic and linoleic acid ethyl esters) in plasma were drawn at pre-dose and at 15, 30, 45 min, and 1, 1.5, 2, 3, 4 and 6 h after treatment administration. Urine samples were collected at baseline and at different interval periods (0–2, 2–4, 4–6, 6–12 and 12–24 h) for EtG quantification. Tyrosol and hydroxytyrosol urine concentrations were also measured in this clinical trial. Their relationship with ethanol concentrations have been already published in a previous manuscript (Pérez-Mañá et al., 2015).

Blood (6 ml) was collected in lithium heparin tubes for ethanol analysis. After centrifugation at 1700 g for 10 min at 4°C, plasma was transferred to tubes sealed with a plastic paraffin film and frozen immediately (−20°C) to avoid ethanol vaporization. A second collection blood tube (5 ml) containing ethylenediaminetetraacetic acid and aprotinin was used for determination of FAEEs. It was centrifuged the same way as above, and plasma was stored frozen (−20°C) until analysis.

Urine samples were collected in different recipients and the total amount of urine generated in each time interval was registered. Three aliquots were stored from each time interval at −20°C until analysis.

Ethanol and EtG analysis
DRI® Ethyl Alcohol Assay (Thermo Fisher, Fremont, CA, USA) was used to analyze concentrations of ethanol in plasma with a cut-off of 10 mg/dl.

EtG was measured with liquid chromatography–mass spectrometry using a dilute and shoot approach (see Supplementary materials for further details).

FAEEs analysis
FAEEs plasma concentrations were analyzed by gas chromatography–mass spectrometry. The method of analysis was based on a method previously described (Kulig et al., 2006), with some modifications (see Supplementary materials section).

Statistical analysis
Sample size was determined for Cohort-1 based on the methodology of bioequivalence studies (10 subjects would be needed considering an alpha risk of 0.05, a power of 80%, a 30% of variability and an increase in FAEEs concentrations of at least 40% from placebo). Twelve subjects participated to increase power.

Differences from baseline were calculated for FAEEs concentrations. For FAEEs and ethanol the following experimental pharmacokinetic/pharmacodynamic parameters were calculated: peak concentration (Cmax), the time to reach the maximum concentration (tmax) and the area under the concentration-time curve from 0 to 6 h (AUC0–6h). The AUC values were calculated with the trapezoidal rule. Urinary EtG excretion from 0 to 24 h after administration was calculated as the sum of the total amount excreted during the different collection intervals.

The data of all three cohorts were analyzed together by means of linear mixed models, which take into account the correlation between values obtained in the same subjects. The outcomes of interest were introduced in these models as dependent variables whereas the ethanol dose was introduced as the independent variable. In the case of the AUC0–6h of ethanol, the FAEEs concentrations and the EtG excretion (0–24 h), the relations between the outcome and the ethanol dose were not always linear. For that reason, log-transformations of both outcomes and the ethanol dose were also considered and those models that showed the most adequate fit based on graphical inspection of the corresponding residual plots were used. The analyses for the main outcomes were also performed with the weight-adjusted doses (data not shown).

In addition, Pearson's correlation coefficient was computed to study the association between ethanol and the FAEEs concentrations (AUC0–6h and Cmax) and between the ethanol concentrations (AUC0–6h) and the EtG excretion (0–24 h).
Results were considered statistically significant at P-values < 0.05 and the statistical software package R, version 3.1.1 (R Foundation for Statistical Computing, Vienna, Austria), was used for the analyses. All analyses were conducted with all the participants.

RESULTS

There were no demographic baseline differences among participants in the three different cohorts. Also no overlap between ethanol doses was observed when the dose of ethanol was adjusted to weight of individuals.

Ethanol

There were no positive baseline samples for ethanol. Ethanol plasma concentrations and pharmacokinetic parameters calculated (AUC_{0-6h}, C_{max}, t_{max}) increased with the ethanol administered dose (see Fig. 1). High variation in ethanol concentrations was found as the coefficient of variation (CV) of the AUC among individuals with the same dose ranged from 11.6 to 40.2%. Furthermore, a non-linear relationship was found between AUC of ethanol concentrations and alcohol dose. The relationship was linearized after the log-transformation of both outcomes. As a summary the pharmacokinetic parameters estimated for each dose of ethanol are presented in Table 1.

Ethyl glucuronide

Concentrations in spot urine samples collected before drinking were below lower limit of quantification (LLOQ) with the exception of four samples of three different subjects (values between 0.5 and 2.8 µg/ml). EtG was mainly excreted in the period from 0 to 6 h for 6 g; 4–6 h for 12 g, 6–12 h for 18 g, 12–24 h for 24 g, finally by the period from 12 to 24 h. EtG recovery (0–24 h) showed a dose-dependent relationship with ethanol administered doses. This relationship follows an exponential trend as it can be seen in Fig. 2. The logarithm of the recovery of EtG increased linearly as a function of the logarithm of the ethanol dose (log-dose); on average, augmenting the log-dose by one unit, the log-recovery increased by 1.65 units per gram of alcohol (95% CI: [1.49, 1.82]; P < 0.001). The relative percent (molar equivalent) of ethanol excreted in the urine as EtG the first 24 h ranged from 0.004 to 0.031% in our study. The values also increased with alcohol administered dose (see Fig. 2).

![Fig. 1. Ethanol plasma concentrations. Ethanol plasma concentrations from 0 to 6 h after ethanol administration.](image_url)

**Table 1. Ethanol and non-oxidative metabolites concentrations.**

<table>
<thead>
<tr>
<th>Dose (g)</th>
<th>C_{max} (µmol/ml)</th>
<th>C_{max} (ng/ml)</th>
<th>AUC_{0-6h} (µmol×h/ml)</th>
<th>AUC_{0-6h} (ng×h/ml)</th>
<th>EtG Excretion (0–24 h) (µmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.8 (1.3–4.3)</td>
<td>5.4 (2.6–4.6)</td>
<td>1.4 (1.2–1.6)</td>
<td>3.3 (2.0–4.1)</td>
<td>7.1 (5.2–9.5)</td>
</tr>
<tr>
<td>12</td>
<td>2.5 (1.8–3.4)</td>
<td>4.8 (4.4–5.5)</td>
<td>6.8 (5.8–8.7)</td>
<td>15.6 (13.1–18.2)</td>
<td>22.2 (14.6–35.6)</td>
</tr>
<tr>
<td>18</td>
<td>2.1 (1.6–2.7)</td>
<td>6.6 (5.1–8.1)</td>
<td>10.5 (9.4–12.1)</td>
<td>27.0 (23.1–31.0)</td>
<td>34.4 (28.5–40.3)</td>
</tr>
<tr>
<td>24</td>
<td>2.6 (1.9–3.2)</td>
<td>10.3 (7.8–13.4)</td>
<td>18.1 (13.0–23.4)</td>
<td>43.0 (32.2–53.1)</td>
<td>59.0 (41.0–81.4)</td>
</tr>
<tr>
<td>30</td>
<td>3.4 (2.2–4.1)</td>
<td>23.6 (12.9–43.2)</td>
<td>37.6 (26.7–48.5)</td>
<td>84.9 (52.4–124.9)</td>
<td>127.8 (69.6–227.7)</td>
</tr>
<tr>
<td>42</td>
<td>3.8 (2.5–4.7)</td>
<td>48.5 (31.1–75.7)</td>
<td>75.7 (44.2–124.9)</td>
<td>161.0 (95.6–261.0)</td>
<td>203.9 (89.8–426.6)</td>
</tr>
</tbody>
</table>

AUC_{0-6h}: area under the curve from 0 to 6 h after administration. Model-based estimations of the mean (95% prediction intervals) of the pharmacokinetic parameters and EtG excretion as a function of ethanol dose. No values are presented for Linoleic acid ethyl ester since none of the model fits was satisfactory.
EtG excretion within individuals was slightly variable (CVs of EtG excretion for each dose ranged from 21.2 to 34.5%). The correlation between the ethanol concentrations (AUC0–6 h) and the EtG excretion was 0.82 (95% CI: [0.70, 0.90]; P < 0.001). The relationship between AUC0–6 h of ethanol and EtG excretion was linear. The equation of the linear relationship calculated was the following: EtG (µmol) = 3.09 × AUC0–6 h of ethanol (µmol × h/ml) + 14.8.

**Fatty acid ethyl esters**

Palmitic acid and stearic acid ethyl esters were above LLOQ before ethanol ingestion in six subjects and oleic acid ethyl ester in two subjects. For each specific FAEEs, a dose response relationship with ethanol administration was found (see Fig. 3). Linoleic acid ethyl ester concentrations were undetectable for several subjects and doses (were above LLOQ for one subject with 6 and 12 g, 5 subjects with 18 g and 24 g, 7 subjects with 30 g and all subjects with 42 g). FAEEs could be detected till 3 h for doses ≤18 g and till 6 h for higher doses. The concentrations of palmitic acid ethyl ester were higher than concentrations of the other FAEEs. The model-based estimations of the Cmax of the different FAEEs are presented in Table 1. In the case of the palmitic, stearic and oleic acid ethyl esters, the log-logarithm of the Cmax increased linearly as a function of the logarithm of the ethanol dose (log-dose). Augmenting the log-dose by one unit, the logarithm of the Cmax increased, on average, in 1.06 (95% CI: [0.88, 1.24]; P < 0.001), 1.14 (95% CI: [0.93, 1.34]; P < 0.001) and 1.46 units (95% CI: [1.03, 1.89]; P < 0.001), for palmitic, stearic and oleic acid ethyl esters, respectively.

Concerning the AUC0–6 h, the lowest range of the CV among individuals taking the same dose was observed in the case of palmitic acid ethyl ester (13.5–37.5%), whereas the highest range was observed in the case of linoleic acid ethyl ester (67.8–245.0%). The logarithm of the AUC0–6 h of the different FAEEs increased linearly as a function of the logarithm of the ethanol dose (log-dose): on average, augmenting the log-dose by one unit, the log-AUC0–6 h increased by 1.69 units (95% CI: [1.55, 1.83]; P < 0.001) for palmitic acid ethyl ester, by 1.82 units (95% CI: [1.60, 2.04]; P < 0.001) for stearic acid and by 2.25 units (95% CI: [1.84, 2.66]; P < 0.001) for oleic acid. Model-based estimations of the AUC0–6 h of the different FAEEs are presented in Table 1.

In the case of linoleic acid ethyl ester pharmacokinetic parameters, all models fitted showed a statistically significant increase of both measures as a function of the alcohol dose (P < 0.001 in all cases), but none of the model fits was satisfactory. For this reason, no model-based estimations of both pharmacokinetic parameters are provided.

For palmitic, stearic and oleic acid ethyl ester median time to reach Cmax was 30 min for doses ≤18 g, and 1 h for higher doses. The AUC0–6 h of the ethanol concentrations in plasma correlated with the AUC0–6 h of the different FAEEs (palmitic acid: r = 0.87 (95% CI: [0.78, 0.93]; P < 0.001); stearic acid: r = 0.88 ([0.81, 0.94]; P < 0.001); oleic acid: r = 0.80 ([0.67, 0.87]; P < 0.001) and linoleic acid r = 0.65 ([0.45, 0.79]; P < 0.001)). The relationship between AUC0–6 h of ethanol and AUC0–6 h of the different FAEEs followed a linear trend, except for linoleic acid. For the most abundant FAEE after ethanol ingestion the equation of the linear relationship was: AUC0–6 h of palmitic acid ethyl ester = 10.33 × AUC0–6 h of ethanol + 26.84. Also high correlation was found between the AUC0–6 h of the ethanol concentrations with Cmax of FAEEs (palmitic acid: r = 0.77 ([0.63, 0.87]; P < 0.001); stearic acid: r = 0.82 ([0.7, 0.89]; P < 0.001); oleic acid: r = 0.68 ([0.49, 0.81]; P < 0.001) and linoleic acid r = 0.62 ([0.4, 0.77]; P < 0.001)).

**DISCUSSION**

The administration of ethanol at low–moderate intoxicating doses (6–42 g) to healthy volunteers produced detectable concentrations of ethanol non-oxidative metabolites (at least till 6 h for several FAEEs and ethanol doses and at least till 24 h for EtG). FAEEs concentrations (AUC0–6 h, Cmax) and EtG excretion (0–24 h) showed high correlation with the ethanol administered dose. Both increased with ethanol administered dose and their formation rates do not seem to follow a linear trend. On the other hand the relationship between AUC0–6 h of ethanol and metabolites’ concentrations was linear.

**Ethanol concentrations**

Ethanol concentrations were similar to those obtained in previous studies (Rangno et al., 1981; Holford, 1987; Hoiseth et al., 2007). Ethanol accumulation with dose (disproportionate increase in AUC) can be attributed to changes in hepatic extraction ratio with concentration and to capacity-limited elimination (Holford, 1987).

**Ethyl glucuronide**

EtG urinary excretion increased with the ethanol dose and as expected the highest recovery in urine was obtained with 42 g.
Although only <1% of the ethanol ingested is metabolized in humans to EtG (Politi et al., 2007) we have found a very high correlation between ethanol dose and EtG excretion. The disproportionate increase in EtG urinary excretion in relation to alcohol dose has been already described (Rosano and Lin, 2008; Jatlow et al., 2014). A similar trend in the relationship has been described in blood as the AUC of EtG was triplicated (2.43 vs. 8.58 mg × h/l) after just doubling the ethanol administered dose (0.5 g/kg vs. 1 g/kg) (Høiseth et al., 2010). Saturation of ethanol major metabolic pathway (ADH) and greater substrate availability for conjugation routes as the dose increases explains the results obtained (Rosano and Lin, 2008; Jatlow et al., 2014).

Inter-individual variability found in EtG formation in subjects taking the same dose may be explained by genetics and nutritional factors. The glucuronidation of ethanol through UGTs is produced mainly by UGT1A1 and 2B7 (Politi et al., 2007). Additionally, diet components like flavonoids may influence the conversion of ethanol to EtG through UGT competitive inhibition (Schwab and Skopp, 2014). EtG formation follows a Michaelis-Menten kinetics (also the ethanol oxidation to acetaldehyde by ADH) so ethanol concentrations available in each subject modulate the formation rate of EtG. Furthermore, the presence of polymorphisms coding the enzymes of ethanol oxidative metabolism could explain differences between subjects (Jatlow and O’Malley, 2010).

**Fatty acid ethyl esters**

FAEES determined in our study were those predominant in plasma after ethanol ingestion (Dan and Laposata, 1997; Politi et al., 2007). Inter-individual variability detected in FAEES concentrations was higher than for EtG. Individual differences can be attributed to the different activity of the enzymes responsible for FAEES synthesis or metabolism, but probably also to plasma triglyceride levels as a source of fatty acids for FAEES synthesis (Dan and Laposata, 1997; Soderberg et al., 1999). The concentration of saturated and mono-unsaturated FAEES showed a very high correlation with ethanol administered dose (Soderberg et al., 1999). On the other hand, the concentrations of the polyunsaturated linoleic acid ethyl ester showed a poorer correlation. The explanation can be related to the fact that linoleic acid is an essential fatty acid that is available only through diet, while palmitic, oleic and stearic acid are also obtained.
through metabolism. Breakfast 2 h after ethanol administration can justify the small rise in linoleic acid ethyl ester concentrations at 4 h.

The plasmatic FAEEs limited detection period (6 h) after ethanol doses compatible with social consumption, in comparison with 24 h for EtG, and the long lasting elevations of FAEEs that have been reported in heavy drinkers, due to diffusion from adipose tissue (Bisaga et al., 2005), makes urinary EtG more suitable to routinely monitor ethanol abstinence.

To the best of our knowledge, this is the first study reporting the lack of linearity in the relationship between ethanol dose and FAEEs plasma concentrations. The explanation could be the same than for lack of linearity in the relationship between ethanol dose and FAEEs (Best et al., 2006).

It should be noted that the non-linearity in the concentrations of both non-oxidative metabolites of alcohol (urinary EtG and plasmatic FAEEs) has been observed at relatively low doses of alcohol.

Strengths and limitations

The crossover design allowed the same subjects to be treated with at least two different doses. However, not all subjects received all doses and some comparisons were indirect. We enrolled only male volunteers for avoiding potential sex differences in alcohol and FAEEs pharmacokinetics (FAEEs formation can be 2-fold greater in men, according to Soderberg et al., 1999). Future studies with a larger sample size per dose should include women. The 3-day period between sessions was not enough to achieve a complete wash-out in some subjects although some FAEE could be endogenously formed. Furthermore, higher doses of ethanol should be included to confirm the trend observed in FAEE concentrations. Experimental sessions could not be planned long enough to provide a complete blood EtG pharmacokinetic profile. For this reason, we decided to measure EtG only in urine, which was valuable to quantify the amount of ethanol excreted as EtG.

CONCLUSION

After administering low to moderate doses of ethanol to healthy male subjects the formation rate of EtG and FAEEs does not seem to follow a linear trend and this observation should be taken into account when interpreting results in biological matrices in clinical and forensic settings.

SUPPLEMENTARY MATERIAL

Supplementary material is available at Alcohol And Alcoholism online.

ACKNOWLEDGEMENTS

We want to thank R. Pardo-Louzano, C. Mustata, M. Pérez, S. Martín, C. Gibert their contribution in the conduct of the experimental sessions.

FUNDING

This work was supported by Fondo de Investigación Sanitaria (FIS)-Instituto de Salud Carlos III (ISCIII)-Fondo Europeo de Desarrollo Regional (FEDER) [FIS PI081913 and RTA RD12/0028/0009], ISCIII-FIS-Consorcio de Apoyo a la Investigación Biomédica en Red (CAIBER) [CAI08/01/0024], Centro de Investigación Biomédica en Red de la Fisiopatología de la Obesidad y Nutrición (CIBEROBN) [CB06/03/0028], Plan Nacional sobre Drogas (2013062), Departamento de Innovación, Universidades y Empresa (DUIE) de la Generalitat de Catalunya [2014SGR 680] and ISCIII Rio Hortega and Juan Rodés contract (CM12/00085 and JR 15/00005 for CPM).

CONFLICT OF INTEREST STATEMENT

None declared.

REFERENCES


