The effect of test meal monounsaturated fatty acid:saturated fatty acid ratio on postprandial lipid metabolism

Helen M. Roche¹*, Antonis Zampelas², Kim G. Jackson³, Christine M. Williams³ and Michael J. Gibney¹

¹Unit of Nutrition, Trinity Centre for Health Sciences, St James’s Hospital, James’s Street, Dublin 8, Ireland
²School of Biological Sciences, University of Surrey, Guildford GU2 5XH, UK
³Hugh Sinclair Unit of Human Nutrition, Department of Food Science and Technology, University of Reading, Reading RG6 6AP, UK

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Epidemiological evidence shows that a diet high in monounsaturated fatty acids (MUFA) but low in saturated fatty acids (SFA) is associated with reduced risk of CHD. The hypocholesterolaemic effect of MUFA is known but there has been little research on the effect of test meal MUFA and SFA composition on postprandial lipid metabolism. The present study investigated the effect of meals containing different proportions of MUFA and SFA on postprandial triacylglycerol and non-esterified fatty acid (NEFA) metabolism. Thirty healthy male volunteers consumed three meals containing equal amounts of fat (40 g), but different proportions of MUFA (12, 17 and 24% energy) in random order. Postprandial plasma triacylglycerol, apolipoprotein B-48, cholesterol, HDL-cholesterol, glucose and insulin concentrations and lipoprotein lipase (EC 3.1.1.34) activity were not significantly different following the three meals which varied in their levels of SFA and MUFA. There was a significant difference in the postprandial NEFA response between meals. The incremental area under the curve of postprandial plasma NEFA concentrations was significantly (P = 0.03) lower following the high-MUFA meal. Regression analysis showed that the non-significant difference in fasting NEFA concentrations was the most important factor determining difference between meals, and that the test meal MUFA content had only a minor effect. In conclusion, varying the levels of MUFA and SFA in test meals has little or no effect on postprandial lipid metabolism.

Fat intake: Monounsaturated fatty acids: Saturated fatty acids: Postprandial metabolism

An elevated postprandial lipaemic response is increasingly being recognized as an important risk factor for the development of CHD. Patients with CHD show a more prolonged postprandial triacylglycerolaemic response compared with healthy controls (Patsch et al. 1993) and the concentration of postprandial chylomicron remnant apolipoprotein (apo) B-48 has been directly related to the progression of atherosclerosis (Karpe et al. 1994). Recent prospective evidence has shown that non-fasting triacylglycerol concentrations are a significant predictor of future myocardial infarction (Stampfer et al. 1996) which further supports the hypothesis that impaired postprandial plasma triacylglycerol metabolism plays a causal role in the development and progression of CHD. The causal nature of this relationship is based on the central role of triacylglycerol-rich lipoprotein (TRL) metabolism, which influences the composition and metabolic fate of other lipid and lipoprotein fractions. TRL are atherogenic lipoproteins in their own right. Moreover, elevated postprandial TRL concentrations promote the catabolism of the cardio-protective HDL fraction, promote the formation of the highly atherogenic small dense LDL fraction (Roche & Gibney, 1995) and influence plasma non-esterified fatty acid (NEFA) metabolism.

Although much of the interest in postprandial lipid metabolism has focused on the adverse consequences of elevated TRL, elevated plasma NEFA concentrations have been proposed as a risk marker of CHD (Frayn et al. 1996). Plasma NEFA and triacylglycerol metabolism are closely linked, both in the fasting and postprandial states. In the

Abbreviations: apo, apolipoprotein; AUC, area under the curve; IAUC, incremental area under the curve; MUFA, monounsaturated fatty acids; NEFA, non-esterified fatty acids; SFA, saturated fatty acids; TPL, triacylglycerol-poor lipoprotein; TRL, triacylglycerol-rich lipoprotein.

*Corresponding author: Dr Helen M. Roche, fax +353 1 454 2043, email hmroche@tcd.ie
fasting state, NEFA are released into the circulation from the hydrolysis of adipose tissue triacylglycerol; this is controlled by hormone-sensitive lipase (EC 3.1.1.3) activity (Coppack et al. 1994). Immediately following meal ingestion, plasma NEFA concentrations decline because insulin inhibits hormone-sensitive lipase activity, thereby preventing the release of NEFA from adipose tissue (Frayn et al. 1994). Following the initial fall in postprandial NEFA concentrations, plasma concentrations return to pre-meal concentrations. Much of this increase is due to reduced suppression of hormone-sensitive lipase with decreasing insulin concentration. In addition, a significant proportion (perhaps up to 50%) of the hydrolysed postprandial TRL fatty acids are not taken up into adipose tissue but ‘spill over’ into the circulation as NEFA, thus increasing plasma NEFA concentrations (Binnert et al. 1996). Plasma NEFA concentrations are the primary substrate for hepatic very-low-density lipoprotein (VLDL)-triacylglycerol synthesis; elevated NEFA concentrations induce hepatic VLDL synthesis thereby contributing to raised plasma triacylglycerol concentrations (Byrne et al. 1991). In view of the close metabolic relationship between NEFA and triacylglycerols, and their effect on the development and progression of CHD, dietary factors which modulate postprandial lipid metabolism need investigation. Virtually nothing is known of the effect of meal fat composition on postprandial NEFA metabolism. A large number of studies have evaluated the effect of fat composition on postprandial triacylglycerol metabolism (Weintraub et al. 1988; De Bruin et al. 1993; Zampelas et al. 1994), but have not measured NEFA.

Epidemiological evidence shows a low prevalence of CHD in Mediterranean regions (Keys et al. 1986) where the consumption of monounsaturated fatty acids (MUFA) is relatively high (Kafatos & Mamalakis, 1993). The apparent cardio-protective effect of MUFA can only be partly explained by the hypocholesterolaemic effect of MUFA when substituted for saturated fatty acids (SFA) (Mensink & Katan, 1989; Mensink, 1992); another possibility lies in their ability to modulate the postprandial lipaemic response. Therefore, the present study was designed to determine whether increasing meal MUFA content, at the expense of SFA, affects postprandial lipid metabolism, in an effort to explain the lower rates of CHD observed in populations consuming high amounts of MUFA.

Methods

Subjects

This study was approved by the Ethics Committee of the Federated Dublin Voluntary Hospitals in Ireland and the Royal Surrey County Hospital in the UK, and the trial was conducted on an out-patient basis. Subjects gave written consent before participation in the trial. Thirty healthy male volunteers aged 22.8 (SD 2.9) years, weighing 74.0 (SD 8.3) kg and with a mean BMI of 22.9 (SD 1.5) kg/m² participated in the trial. The subjects were of stable body weight, habitually consumed between 34 and 45% energy as fat, were not adhering to a special diet and were not regular consumers of n-3 polyunsaturated fatty acid supplements or any other nutritional supplement. All participants were non-smokers, did not exercise excessively (>90 min/week) and were not being prescribed any medications.

Test meal composition

The acute test meals provided varying amounts of MUFA and SFA which reflected the fatty acid compositions of the typical northern European and traditional Cretan diets (Gregory et al. 1990; Kafatos & Mamalakis, 1993). The medium-MUFA meal provided MUFA and SFA at levels typical of the current Athenian dietary fat composition. The test meal consisted of 135 g white bread, 36 g strawberry jam and a milk-shake consisting of 40 g of the test oil, 40 g dried skimmed milk powder (Tesco, Cheshunt, UK) and 40 g Nesquik strawberry flavoured milk-shake mixture (Nestlé, Vevey, Switzerland), mixed with 200 ml water (Evian, France). The fatty acid composition of the test meal is presented in Table 1. Subjects were randomly allocated to receive the high-, medium- and low-MUFA test meals once monthly for three consecutive months.

Postprandial investigations

Postprandial investigations of fifteen volunteers were completed at two centres, Trinity College Dublin and the University of Surrey. Plasma samples were re-distributed for central analysis. Each postprandial study began at between 07.30 and 08.00 hours following a 12 h overnight fast. All subjects abstained from alcohol consumption and refrained from strenuous exercise for 24 h before the postprandial investigation. During postprandial investigations subjects abstained from food (including chewing gum) and drinks, with the exception of caffeine-free, low-energy (<4.2 kJ/ml) drinks, e.g. decaffeinated black coffee, sugar-free drinks and water.

A 21 gauge, 32 mm venous catheter (Abbott Ireland Ltd, Dublin, Ireland) was inserted into the subject’s antecubital vein of the non-dominant forearm. To ensure that the cannula remained patent throughout the 9 h study period it was flushed with sodium citrate in saline solution (Phoenix

<table>
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<tr>
<th>Test meal</th>
<th>SFA</th>
<th>MUFA</th>
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<tbody>
<tr>
<td>Low-MUFA</td>
<td>20.0</td>
<td>14.0</td>
<td>5.7</td>
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<tr>
<td>Medium-MUFA</td>
<td>14.6</td>
<td>20.0</td>
<td>5.4</td>
</tr>
<tr>
<td>High-MUFA</td>
<td>6.3</td>
<td>28.3</td>
<td>5.4</td>
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SFA, saturated fatty acids; MUFA, monounsaturated fatty acids, PUFA, polyunsaturated fatty acids.
Pharmaceuticals Ltd, Gloucester, Glos., UK). Two fasting blood samples (−10 and 0 min) were drawn before the test meal was consumed. The test meal was consumed under supervision to ensure that all food was eaten within a 20 min period. Postprandial blood samples were drawn every hour for 9 h. Blood samples were centrifuged (2000 g) immediately, the plasma was harvested and divided into two portions. One portion of plasma was vortex-mixed, divided into portions and frozen (−20 °C) immediately for subsequent analysis. The remaining plasma was used to prepare TRL and triacylglycerol-poor lipoprotein (TPL) fractions using the ultracentrifugation method, as previously described (Grundy & Mok, 1976; Zampelas et al. 1994). This plasma was stored (<5 °C) for 24 h, and ultracentrifugation was completed on the day after blood collection. Triacylglycerol, cholesterol and apoB-48 analysis was completed on each of these fractions as well as plasma.

After 9 h postprandial post-heparin lipoprotein lipase (EC 3.1.1.34) activity and hepatic lipase activity (EC 3.1.1.3) were determined following the infusion of 7500 IU heparin sodium (Multiparin Heparin Injection (5000 IU/ml), CP Pharmaceuticals Ltd, Wrexham, Clwyd, UK). Blood samples were drawn 5 min and 15 min following heparin injection. The blood samples were centrifuged (2000 g) immediately and the plasma was harvested, divided into portions and frozen (−70 °C) immediately for subsequent analysis. Fasting post-heparin lipoprotein lipase and hepatic lipase activities were also determined on a separate occasion, following an overnight fast (12 h).

**Biochemical variables investigated**

All analysis was completed within 12 months of the blood samples being drawn. Analysis of plasma, TRL and TPL-triacylglycerol (TAG PAP Uni-kit, Roche Diagnostics Ltd, Vevey, Switzerland), cholesterol (Cholesterol PAP Uni-kit, Roche Diagnostics Ltd) and NEFA (NEFA c Kit (ACS ACOD method), Wako Chemicals GmbH, Neuss, Germany) concentrations were determined using enzymic colorimetric assays on a Cobas-Bio centrifugal analyser (Cobas Mira, Roche Diagnostics Ltd). The inter-assay CV, measured with with external control plasma were 5.05 % for plasma triacylglycerol, 3.66 % for TRL-triacylglycerol, 4.85 % for plasma cholesterol and 8.58 % for plasma NEFA.

ApoB-48 concentrations in plasma and the TRL fraction were determined using a competitive ELISA described previously (Lovegrove et al. 1996), using a specific polyclonal anti-apoB-48 antisera (Peel et al. 1993). The inter-assay CV was 8.8 % for 3.987 μg/ml.

Lipoprotein lipase activity was determined using triolein as a substrate, by the method previously described (Nilsson-Ehle & Schotz, 1976). Briefly, a triolein emulsion was diluted with 50 mM-Tris (containing 3 g bovine serum albumin/l and either 0.2 M-NaCl or 4 M-NaCl and 2 U heparin/ml) and pre-incubation with inactivated human serum. Incubations of 20 μl plasma with the emulsion were carried out for 30 min at 37 °C. A milk lipoprotein lipase standard was used to evaluate the assay. The inter-assay CV, using a single emulsion, was 5.06 % for 12 800 mU/ml.

**Statistical analysis**

All statistical analyses were completed with the Apple Macintosh-compatible statistical package Data Desk 4.1 (Data Description Inc., New York, NY, USA). Two fasting samples were analysed for all biochemical variables and the mean of these two values was used for statistical analysis. Plasma triacylglycerol, TRL-triacylglycerol and plasma apoB-48 concentrations were transformed to the natural log (ln) to give the data a normal Gaussian distribution. Repeated-measures ANOVA, with meal MUFA level as the independent variable, was employed to investigate differences in the postprandial response between meals.

The postprandial data were expressed in summary form, i.e. area under the postprandial response curve (AUC), the incremental area under the postprandial response curve (IAUC), maximum postprandial levels and time to maximal postprandial levels were used to investigate between-meal postprandial variations (Matthews et al. 1990). Two-way ANOVA, using subject and meal as the independent variables, was used to investigate significant differences of these summary variables. Post-hoc statistical analysis was completed using the least significance difference, to determine significant differences between group means (Snedecor & Cochran, 1989).

**Results**

Postprandial plasma triacylglycerol, TRL-triacylglycerol and plasma apoB-48 concentrations following the three test meals are presented in Fig. 1. Repeated-measures ANOVA showed that plasma triacylglycerol, TRL-triacylglycerol and apoB-48 concentrations increased significantly (P = 0.0001) following all three test meals. However there was no significant difference in the postprandial responses between the three test meals. A bi-phasic postprandial response was observed following all meals. ApoB-48 concentrations in the TRL and TPL were not significantly different between meals, therefore the results are not shown. The AUC, maximum postprandial plasma concentrations and time to maximum postprandial plasma triacylglycerol concentration of postprandial plasma triacylglycerol, TRL-triacylglycerol and apoB-48 concentrations were not significantly different between meals.

The changes in plasma NEFA concentrations during the postprandial response following the three test meals are presented in Fig. 2(a). Plasma NEFA concentrations were significantly (P = 0.0001) reduced following meal ingestion and returned to near fasting levels 6 h postprandially. There was a significant (P = 0.019) difference in the postprandial plasma NEFA response between meals, plasma NEFA concentrations were reduced to a lesser extent following the high-MUFA meal. Fasting NEFA concentrations and the IAUC of postprandial plasma NEFA concentrations are presented in Fig. 2(b). Fasting plasma NEFA concentrations were different, but not significantly, before the test meals, while the postprandial NEFA IAUC was significantly
Fig. 1. Postprandial concentrations of (a) plasma triacylglycerol, (b) triacylglycerol-rich lipoprotein (TRL)-triacylglycerol and (c) plasma apolipoprotein (apo) B-48 following test meals containing high (●), medium (○) and low (△) levels of monounsaturated fatty acids. Values are means for thirty subjects, with their standard errors represented by vertical bars.

Fig. 2. (a) Change in postprandial plasma non-esterified fatty acid (NEFA) concentrations and (b) fasting NEFA concentrations (■) and incremental areas under the postprandial NEFA curves (□) following test meals containing high (●), medium (○) and low (△) levels of monounsaturated fatty acids (MUFA). Values are means for thirty subjects, with their standard errors represented by vertical bars.

(P = 0.0332) lower following the high-MUFA meal. Stepwise multiple regression analysis showed that fasting plasma NEFA concentration (β = 5.81; P = 0.0001), followed by fasting plasma triacylglycerol concentrations (β = 0.735; P = 0.078), hepatic lipase activity (β = 0.006; P = 0.025) and meal MUFA content (β = 0.182; P = 0.078) were the factors which determined the postprandial NEFA IAUC.

Postprandial plasma glucose, insulin, total plasma cholesterol and HDL-cholesterol concentrations were not significantly different between meals, therefore these results are not presented. Mean postprandial post-heparin lipoprotein lipase activities were not significantly different following the high-, medium- and low-MUFA test meals (334 (SD 13), 342 (SD 13), 327 (SD 12) mU/ml respectively).
Discussion

The postprandial lipaemic response is known to affect the pathogenesis and progression of CHD (Groot et al. 1991; Karpe et al. 1994). The magnitude of this response is affected by physiological factors including fasting lipid concentrations, age, sex, body weight and lipoprotein lipase activity (Roche & Gibney, 1995). Dietary factors, particularly habitual dietary fat composition and the composition of fat in the test meal have been shown to affect the magnitude of the postprandial triacylglycerol response (Weintraub et al. 1988; De Bruin et al. 1993; Zampelas et al. 1994), but these studies did not measure the postprandial NEFA response. The present study investigated whether changing the proportions of MUFA and SFA in acute test meals affected postprandial triacylglycerol and NEFA metabolism. The test meals used in the present study were designed to reflect habitual dietary fatty acid composition in northern and southern Europe (Gregory et al. 1990; Kafatos & Mamalakis, 1993), thereby investigating the biochemical basis of the beneficial effect associated with the southern European diet, which is rich in MUFA. The present study clearly demonstrated that the replacement of SFA with MUFA in acute test meals does not influence postprandial plasma triacylglycerol, TRL-triacylglycerol, apoB-48, insulin, glucose and cholesterol concentrations or post-heparin lipoprotein lipase activity. The results of this experiment are important and noteworthy because the effect of acute test meals which provide different proportions of MUFA and SFA on postprandial lipid metabolism has never been investigated. Furthermore there were two aspects of the study which merit discussion: first, a consistent bi-phasic triacylglycerol response was shown; second, the mean MUFA content may have affected postprandial NEFA metabolism.

In the present study all subjects showed a consistent bi-phasic postprandial triacylglycerolaemic response, irrespective of test meal fatty acid composition. Studies investigating the effect of ingesting a single test meal following an overnight fast usually show a non-phasic triacylglycerol response (Roche & Gibney, 1996), whilst meals consumed midday or in the early evening cause a bi-phasic triacylglycerol response, the first peak being attributed to the previous meal and the second peak representing the triacylglycerol of the test meal (Zampelas 1994; Fielding et al. 1996). In the present study subjects had fasted overnight for at least 12 h, therefore it is unlikely that the early triacylglycerol peak could have been derived from their previous meal. The second triacylglycerol peak could have been due to hepatically-derived VLDL secretion, which occurs 4–5 h following meal ingestion (Schneeman et al. 1993). The test meals contained fructose, which is known to increase the postprandial triacylglycerol response (Jeppsen et al. 1995) by stimulating hepatic VLDL production (Cohen & Schall, 1988). Therefore the fructose component of the test meal could have contributed to the second triacylglycerol peak. A recent study in this laboratory investigated this hypothesis by comparing the effect of a test meal identical to that used in the present study with one that provided the same amount of fat but a lower level of carbohydrate (136 v. 17 g) (Shishehbor, 1997). The high-carbohydrate meal (like that used in the present study) evoked a mean bi-phasic response, while the low-carbohydrate meal evoked a mono-phasic triacylglycerol response. Therefore the carbohydrate component of the test meal represents the most likely explanation for the consistent bi-phasic response seen in this study.

In conclusion, this study shows that the replacement of SFA with MUFA in acute test meals does not affect postprandial TRL metabolism. There may have been a small effect on postprandial NEFA metabolism, but the extent of this could not be clearly defined due to the non-significant difference in fasting plasma NEFA concentrations before the test meals.

Acknowledgement

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References


