The degree of saturation of fatty acids influences post-ingestive satiety*

Clare L. Lawton†, Helen J. Delargy, Justine Brockman, Fiona C. Smith and John E. Blundell

BioPsychology Group, School of Psychology, University of Leeds, Leeds LS2 9JT, UK

(Received 5 February 1999 – Revised 12 August 1999 – Accepted 6 October 1999)

Two studies were designed to compare the effects on post-ingestive satiety of manipulating the degree of saturation of fatty acids, at a fixed chain length (18 C atoms), in a fixed energy (5·68 MJ for males; 3·97 MJ for females), high-fat (55 % energy) lunch meal. Two different groups of twenty subjects (ten males and ten females) took part in each study. All forty subjects were of normal weight and aged between 18 and 36 years. Study 1 compared the effects of fat A (oleic blend, high in monounsaturated fatty acids (MUFA)) with those of fat B (linoleic blend, high in polyunsaturated fatty acids (PUFA)) and fat C (stearic–oleic blend, high in saturated fatty acids (SFA)). Study 2, which was designed to confirm and extend the findings of Study 1, compared the effects of fats A, B and C with those of fat D (a linoleic–oleic blend). Energy and nutrient intakes were monitored for the rest of the day and for the following day. Profiles of hunger, fullness and other sensations were monitored by continuous tracking and end-of-day questionnaires. In each meal the fat content was exclusively composed of one particular type (A, B, C or D) and was divided equally between the main course and dessert. Study 1 revealed a significant effect of fat type (degree of saturation) on intake of nutrients at the following (dinner) meal (smallest F[2,36] 3·38, $P < 0·05$), on post-ingestive ratings of motivation to eat (smallest F[2,36] 4·18, $P = 0·02$) and on energy intake over the whole test day (F[2,36] 3·39, $P < 0·01$). Subjects consumed significantly more energy after consumption of the lunch containing fat A than after the lunches containing fats B or C and there was a trend for these effects to continue into the second day. In Study 2, fat C produced more similar effects on appetite to fat A and there was a tendency for subjects to consume more over the whole test day when they had consumed the lunch containing fat A than when they had consumed the lunch containing fat B. Furthermore, when the data from fat conditions A and B in both studies were combined (n 40) the results of Study 1 were confirmed. Overall, the results of these short-term studies indicate that PUFA may exert a relatively stronger control over appetite than MUFA and SFA.

Fatty acids: Fat saturation: Satiety

In recent years it has been demonstrated that foods containing a high percentage of fat have the capacity to promote overconsumption in obese (Lawton *et al*. 1993) and lean subjects (Green *et al*. 1994). In addition, studies using controlled fat intakes have indicated that fat has a weaker effect on satiety, joule for joule, than carbohydrate or protein (e.g. '…joule for joule the high-fat preloads suppressed intake at lunch less than did the high-carbohydrate preloads'. Rolls *et al*. 1994). The overconsumption effect of fat is almost certainly due to the high energy density of high-fat foods (Stubbs *et al*. 1995*b*; Blundell & MacDiarmid, 1997) but the somewhat weaker effect on post-ingestive satiety is probably due to the physiological action of fat in generating inhibitory satiety signals. The induction of physiological satiety signals may well depend on the composition of fatty acids in the particular fats used.

Two prominent features of fatty acids are their chain length and degree of saturation. Although a number of human studies have compared the effects of different chain length fatty acids on food intake (e.g. Rolls *et al*. 1988; Stubbs & Harbron, 1995), investigation of the effects of degree of saturation of fat appears to have been neglected. However, some studies do indicate physiological satiety mechanisms through which the degree of saturation of dietary fat in a meal could influence subsequent intake. Potential mechanisms involving the putative satiety hormone cholecystokinin (CCK), the oxidative capacity of ingested fat and the neurotransmitter 5-hydroxytryptamine (5-HT; serotonin) have been suggested respectively by the

Abbreviations: CCK, cholecystokinin; HARU, Human Appetite Research Unit; 5-HT, 5-hydroxytryptamine; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids; VAS, visual analogue scale.

* Some of the results in this paper were presented as a President's poster at the 8th European Congress on Obesity, Dublin, 18–21 June 1997.

† **Corresponding author:** Dr Clare Lawton, fax +44 (0) 113 233 5749, email ClareL@Psychology.Leeds.ac.uk

work of Beardshall *et al*. (1989), Friedman *et al*. (1986) and Mullen & Martin (1992). Consequently, there is good evidence that fatty acids varying in degree of saturation exert different effects on physiological processes believed to be involved in the control of satiety and eating behaviour. The two studies described in the present paper were carried out as a further contribution to understanding the effect of fatty acid structure on satiety in human subjects.

The experiments were designed to determine the relative contribution to post-ingestive satiety of fats with a constant fatty acid chain length but varying in degree of saturation. The test fats used contained a high proportion of mono-unsaturated fatty acids (MUFA) (oleic blends), polyunsaturated fatty acids (PUFA) (linoleic blends), unsaturated fatty acids (oleic–linoleic blend) or saturated fatty acids (SFA) (stearic–oleic blends) and were incorporated into a fixed-energy lunch meal. The fixed meal design, which measures effects on satiety, was employed (rather than the alternative concurrent evaluation design, which measures effects on satiation) since there was no rationale for believing that there would be any differential effects of the test fats on satiation. The fat content of each lunch meal was, almost exclusively, composed of one of the test fats and provided 55 % of the meal energy. This high fat load was chosen in order to optimize the chances of detecting post-ingestive differences between the test fats. In order to control for any effects of fatty acid chain length on satiety, all test fats were composed, as far as possible, of fatty acids of a chosen fixed chain length (18 C atoms). Study 2 was designed to confirm and extend the findings of Study 1. The results indicate that the fatty acid composition of high-fat foods can influence the degree of post-ingestive satiety.

Methods

Subjects

Study 1. Twenty healthy, normal-weight subjects (ten males and ten females) were recruited from the University staff and student population. All subjects had a BMI between 19 and 26 kg/m^2 (mean 23 kg/m^2) and were aged between 19 and 36 years (mean 24 years).

Study 2. A further twenty healthy, normal-weight subjects (ten males and ten females) were recruited from the University staff and student population. All subjects had a BMI between 19 and 26 kg/m^2 (mean 22 kg/m^2) and were aged between 18 and 33 years (mean 21 years). None of the subjects participating in Study 2 had participated in Study 1.

Both studies. All subjects were screened before recruitment to ensure that they were non-dieters using the three-factor eating questionnaire (Stunkard & Messick, 1985). Subjects scoring greater than ten points on the restraint part of this questionnaire were excluded, after debriefing. Before inclusion in the study, subjects completed a questionnaire rating their liking, on a scale of one to ten, for all of the foods to be presented in the study. All foods had to be scored as five or higher.

Study design

Both studies were designed to compare the effects on post-ingestive satiety of manipulating the degree of saturation of fat, at a fixed chain length (18 C atoms), in a fixed energy (5·68 MJ for all males and 3·97 MJ for all females) high-fat (55 % energy, i.e. 83·2 g for males and 58·3 g for females) lunch meal. Experimental studies and data collected from free-living persons indicate that people can consume more than 130 g fat in a single meal and nearly 200 g in a full day (Blundell & MacDiarmid, 1997). The level of fat intake required in the present studies is, therefore, ecologically valid. Effects on the profile of motivation to eat and on the energy intake for the remainder of the day and for the following day were monitored. Energy intake (the eating response) for the remainder of the day was assessed at a later test meal (in which subjects were requested to eat to comfortable fullness from a buffet-style range of foods) and from snack boxes (see p. 482). Energy intake on the following day was assessed using weighed food diary records.

Both studies conformed to a within-subjects, fully repeated measures design. All subjects received each test condition (three in Study 1 and four in Study 2), in a counterbalanced order (Latin square), on a separate test day. Test days were separated by at least 1 week. The number of test conditions in each study corresponded to the number of different test fats studied.

Test fats

Table 1 shows the fatty acid compositions of the test fats used in Study 1 and Study 2.

Study 1. There were three test fat conditions (A, B and C). Fat A was Trisun-80 oil (high in MUFA, oleic blend), fat B was safflower oil (high in diunsaturated fat, linoleic

Table 1. Fatty acid compositions of the test fats (g/100 g total fatty acids)

	Palmitic 16:0	Stearic 18:0	Oleic 18:1	Linoleic 18:2
Study 1				
Fat A: Trisun-80 oil (oleic blend)	4·2	4·2	81·3	8·2
Fat B: safflower oil (linoleic blend)	6·8	2·8	14·0	74·7
Fat C: sheanut oil (stearic–oleic blend)	5·0	39·0	44·0	5·0
Study 2				
Fat A: oleic blend	4·5	4·1	74·5	14·8
Fat B: linoleic blend	6·8	2·7	14·0	74·4
Fat C: stearic–oleic blend	4·3	35·6	45·4	12·9
Fat D: oleic–linoleic blend	5·6	3·5	45·1	43·7

blend) and fat C was sheanut oil (high in SFA, stearic–oleic blend). All three fats contained a high proportion of C_{18} fatty acids and a constant proportion (between 4·2 and 6·8 g/100 g total fatty acids) of palmitic acid (16:0). These fats were chosen on the basis of being readily commercially available whilst providing a good separation of degree of fatty acid saturation.

Study 2. There were four test fat conditions (A, B, C and D). Fats A, B and C corresponded to those used in Study 1. Fat D, the additional test fat in this second study, was a mixture of linoleic and oleic acids. Although this study was designed as a replication of Study 1 (with the addition of an extra test fat condition) it was decided to make some small changes to the fatty acid compositions of fats A and C. This was done in order to improve the comparisons between conditions A, B and C. In doing this, the limit was set by safflower oil (fat B) which is never richer than about 75 g/100 g in linoleic acid. As a consequence fat A (used in Study 1) had to be diluted to approximately 75 g oleic acid/100 g by adding safflower oil. Finally, in order to make the linoleic component of fat C more comparable with that of the new fat A, it was decided to use a manufactured blend rather than the naturally occurring sheanut oil used in Study 1.

Test meals (Studies 1 and 2)

Breakfast. A standard breakfast was given. Subjects were allowed to choose their own breakfast on the first test day from a range of alternatives (cereal with milk and/or toast, butter, jam, marmalade plus a beverage). Subjects were then obliged to consume the same meal on subsequent test days.

Lunch. The nutritional composition of the lunch meals used in these studies is shown in Table 2.

Female subjects were required to eat less food than male subjects such that female portions were 70 % of the male portions. All test meals derived 55 % of their total energy intake from fat but differed in terms of the type of fat (A, B, C or D) that they contained. All lunch meals consisted of a savoury course (pasta with chicken and tomato sauce) followed by a sweet course (chocolate dessert). The fat content of the meal was divided equally between the savoury and sweet courses. All lunch meals were identical in terms of physical appearance, energy density and macronutrient composition and as similar as possible in terms of palatability.

Dinner. This meal consisted of a range of foods of medium palatability, provided in excess portions, from which subjects were asked to eat to comfortable fullness. The nutritional composition of the dinner meal foods is provided in the Appendix (Table 1).

Snack boxes. Following the dinner meal, subjects were given a large food box containing excess portions of a range of pre-weighed snack-type foods from which they could eat for the remainder of the day. Subjects were instructed to eat exclusively from the foods provided, to eat as little or as much as they wished and to return uneaten food together with empty wrappers and containers the following morning. The nutritional composition of the snack-box foods is provided in the Appendix (Table 2).

Procedure (Studies 1 and 2)

Study 1 was conducted during the period from mid-August until the end of October 1994. Study 2 was conducted during the period from the end of February until the beginning of June in the following year.

On each test day (day 1) subjects consumed their standard breakfast in the Human Appetite Research Unit (HARU) between 08.30 and 09.00 hours and did not eat again until lunch. They were, however allowed to consume one cup of tea or coffee during the morning (provided that they continued to do this on all subsequent test days). Subjects returned to the HARU for lunch between 12.30 and 13.00 hours. On arrival they were asked to rate their motivation to eat using 100 mm visual analogue scale (VAS) ratings of hunger, fullness, desire to eat and prospective consumption. The appropriate test lunch meal (A, B, C or D) was then provided. Subjects were instructed to eat all the food provided. VAS were then completed as soon as subjects stopped eating (together with post-lunch palatability ratings), then at 15 min intervals for the first hour and then at hourly intervals until dinner. Subjects were instructed not to eat anything between lunch and dinner but were permitted to consume one cup of tea or coffee as during the morning.

Table 2. Nutritional composition of the high-fat test lunches

Food component	Energy (kJ)	Fat (g)	Protein (g)	Carbohydrate (g)
Male portion				
Pasta twists (49 g dry wt)	669	0·7	5·9	34·6
Vegetable sauce (300 g)	414	0·0	5·7	20·4
Lean chicken breast (50 g, diced)	243	1·6	10·9	0·0
Courgette (60 g, sliced)	42	0·2	1·1	1·1
Test fat (A, B, C or D) (40 g)	1506	40·0	0·0	0·0
Chocolate dessert premix (100 g, contained 40 g test fat)	2427	40·0	10·0	48·0
Water (38 g added to premix)	–	–	–	–
Swiss roll (30 g)	377	0·7	1·2	21·1
Total	5678	83·2	34·8	125·2
Percentage dietary energy		55	10	35
Female portion (70% of male portion)				
Total	3974	58·3	24·3	87·7
Percentage dietary energy		55	10	35

Subjects returned to the HARU between 16.30 and 17.00 hours for dinner. On arrival they completed pre-dinner VAS after which they were presented with the *ad libitum* meal. Subjects were instructed to eat as little or as much as they liked until they felt comfortably full. VAS were completed as soon as subjects stopped eating and then at hourly intervals until retiring and finally, before breakfast on the following day. Before leaving the unit, subjects were given their snack-box (from which to eat for the remainder of the day). They were also given a food diary and a small set of digital weighing scales (with which to weigh and record all food and drink consumed on the following day, day 2). Subjects were also given an end-of-day questionnaire which asked them to indicate (on 100 mm VAS) how anxious, contented, thirsty, hungry and full they had felt across the whole test day and also how often they had experienced strong urges to eat.

Subjects were provided with unlimited drinking water at both lunch and dinner meals. The weights of food items eaten from the *ad libitum* dinner meal and for the whole of day 2 were recorded to the nearest 0·1 g. Snack-box intakes were recorded as the number of portions of each food consumed. Subjects were trained to complete the weighed food diaries by the study dietitian who also reviewed completed food diaries with the subjects when they were returned to the HARU.

Statistical analysis (Studies 1 and 2)

All data were analysed using the statistical package Minitab (version 6; Minitab Inc., State College, PA, USA; for data entry), SAS (version 6.12, 1989–1996; SAS Institute Inc., Cary, NC, USA; ANOVA) and SPSS (version 6.0, 1993; SPSS Inc., Chicago, IL, USA; to calculate statistical power). Energy and macronutrient intakes from each eating episode on day 1 (when all foods were provided by HARU) were calculated using manufacturer's nutritional information. Food diary intakes were analysed using a combination of manufacturer's information and COMP-EAT (version 4.0, Lifeline Nutrition Services, London, UK), a computerized version of the British food tables (Holland *et al.* 1991). All VAS scores were recorded in mm, with an increase in score representing an increase in the measured variable.

The 'before breakfast' ratings on day 2 were analysed by two-way (one repeated measure) ANOVA with lunch meal fat type as the within-subjects variable and subject sex as the between-subjects variable. All other data were analysed by three-way (two repeated measures) ANOVA with time of rating and lunch meal fat type as the within-subject variables and subject sex as the between-subjects variable. *Post hoc* tests between individual means were carried out using Student's *t* tests for paired or unpaired comparisons as appropriate.

Ethical considerations

The studies were approved by the Ethics Committee of the School of Psychology, University of Leeds, Leeds, UK. The informed consent of each subject was obtained in written form. Subjects were given a small honorarium to compensate for their time.

Results

Post-lunch palatability ratings

There were no significant differences between the test meals (containing the different test fats) on mean ratings (n 20) of how tasty, salty, bland, pleasant, filling and satisfying subjects found the test lunch meals in Study 1 and Study 2 (results not shown). The mean scores for tasty and pleasant were well above 50 mm for each test meal indicating that all meals (in both studies) were well liked.

Energy intakes on day 1

The mean (n 20) energy intakes from dinner and the evening snacks and for the whole of day 1 (test meal day, breakfast + lunch + dinner + evening snack) in each study are shown in Table 3.

In Study 1, the differences in the effects of the three test fats on energy consumed from the dinner meal approached significance (F[2,36] 2·72, $P = 0·08$). In this meal and with the evening snacks (F[2,36] 1·15, $P = 0·29$) there was a tendency for subjects to consume more energy after the lunch containing fat A than after the lunches containing fats B or C. Hence analysis of the energy intakes across the whole test day revealed a significant main effect of fat type (F[2,36] 3·39, $P < 0·01$). Paired t tests (d.f. 19) revealed that subjects consumed significantly more energy during the whole test day when they had consumed the lunch containing fat A than when they had consumed the lunch containing fat C (t 2·67, $P = 0·015$).

The four test fats used in Study 2 did not exert any significantly different effects on energy consumed from the dinner meal (F[3,54] 1·67, $P = 0·18$) or from evening snacks (F[3,54] 0·62, $P = 0·60$). Although, as in Study 1, there was a tendency for subjects to consume more energy in these episodes after fat A than fat B, this did not add up to a significant difference between intakes over the whole test day (F[3,54] 0·74, $P = 0·53$).

Macronutrient intakes on day 1

Table 3 also shows the mean (n 20) macronutrient intakes (g) from dinner and the evening snacks and for the whole of day 1 in each study. In Study 1, subjects consumed significantly more protein (g) at dinner (F[2,36] 7·60, $P < 0·01$) and over the whole test day (F[2,36] 7·12, $P < 0·01$) when they had consumed the lunch containing fat A than when they had consumed the lunch containing fat B ($P < 0·01$) or fat C ($P < 0·05$). Similarly, they consumed significantly more carbohydrate (g) at dinner (F[2,36] 3·38, $P < 0·05$) when they had consumed the lunch containing fat A than when they had consumed the lunch containing fat B ($P < 0·05$). They also consumed more carbohydrate (g) over the whole test day (F[2,36] 3·39, $P < 0·05$) when they had consumed the lunch containing fat A than when they consumed the lunch containing fat B ($P < 0·05$) or fat C ($P < 0·05$).

Analysis of the dinner meal intake from Study 2 revealed a significant lunch meal fat type × sex interaction for protein intake (F[3,54] 4·76, $P < 0·01$). Separate analysis of the data from female subjects revealed a significant main effect

Table 3. Energy and macronutrient intakes from dinner, evening snacks and for the whole of day 1, in subjects consuming a standard breakfast and a lunch meal containing a test fat (A, B, C or D)†

(Mean values with their standard errors for twenty subjects)

Test fat . . .	A		B		C		D	
Fat type . . .	Oleic		Linoleic		Stearic–oleic		Oleic–linoleic	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Study 1								
Dinner								
Energy (MJ)	4·4	0·5	3·9	0·3	3·9	0·4		
Fat (g)	49·4	6·4	45·8	5·0	44·7	5·4		
Protein (g)	49·3	4·7	42·6**	3·6	43·3*	3·7		
Carbohydrate (g)	111·1	10·3	95·1*	6·0	98·2	7·6		
Evening snacks								
Energy (MJ)	2·8	0·4	2·6	0·4	2·6	0·4		
Fat (g)	32·7	4·6	31·2	5·2	29·4	4·7		
Protein (g)	16·6	3·4	15·6	3·1	16·5	3·4		
Carbohydrate (g)	81·0	11·0	77·3	10·2	76·7	12·1		
Total day‡								
Energy (MJ)	14·1	0·7	13·4	0·6	13·4*	0·7		
Fat (g)	164·1	8·4	158·9	7·5	156·0	8·5		
Protein (g)	112·9	7·3	105·1*	6·1	106·8*	6·8		
Carbohydrate (g)	381·1	20·2	361·7*	16·3	364·2	19·6		
Study 2								
Dinner								
Energy (MJ)	3·2	0·3	2·9	0·3	3·2	0·3	3·1	0·3
Fat (g)	34·5	4·0	30·0	3·4	32·2	3·7	31·0	3·3
Protein (g)	32·4	3·4	30·0	3·6	32·9	3·6	32·5	3·0
Carbohydrate (g)	84·1	10·8	80·3	9·0	94·4	10·4	86·1	8·2
Evening snacks								
Energy (MJ)	4·1	0·6	4·0	0·7	3·9	0·5	3·7	0·5
Fat (g)	50·7	7·8	47·6	8·2	47·1	7·1	44·4	7·0
Protein (g)	27·5	4·8	26·1	4·7	23·9	4·5	23·2	3·8
Carbohydrate (g)	107·4	17·0	111·8	18·9	108·5	14·2	101·8	13·5
Total day‡								
Energy (MJ)	13·9	0·9	13·6	0·9	13·8	0·8	13·4	0·7
Fat (g)	166·7	12·7	159·1	12·7	161·0	11·7	157·0	11·5
Protein (g)	104·1	8·4	100·4	8·5	101·0	8·2	100·0	7·4
Carbohydrate (g)	375·0	30·7	375·8	29·1	386·5	27·0	371·5	25·4

Mean values were significantly different from those for test fat A: * $P < 0{\cdot}05$, ** $P < 0{\cdot}01$.
† For details of test fats, see Table 1.
‡ Sum of breakfast + lunch (average of male and female portions) + dinner + evening snacks.

of lunch meal fat type (F[3,27] 4·49, $P = 0{\cdot}011$) which was not revealed by separate analysis of data from the male subjects (F[3,27] 1·99, NS). Hence female subjects, but not male subjects, consumed more protein (g) at dinner when they had consumed the lunches containing fat A ($P < 0{\cdot}05$) or fat D ($P = 0{\cdot}012$) than when they had consumed the lunch containing fat B.

Subjective ratings of motivation to eat

(a) Post-lunch to pre-dinner period. All ratings from both studies showed significant main effects of time as would be expected. In Study 1, a main effect of lunch meal fat type (F[2,36] 5·29, $P = 0{\cdot}01$) on ratings of prospective consumption (Fig. 1) indicated that subjects thought they could eat more food after consuming the lunch containing fat A than after consuming the lunch containing fat B ($P < 0{\cdot}05$ at the post-lunch, 45 min and 1 h ratings, $P < 0{\cdot}01$ at the 30 min rating) or fat C ($P < 0{\cdot}01$ at the post-lunch, 30 min and 1 h ratings, $P < 0{\cdot}05$ at the 45 min rating).

Similar results were obtained for ratings of desire to eat (F[2,36] 4·77, $P = 0{\cdot}0146$; A > B and C) and fullness

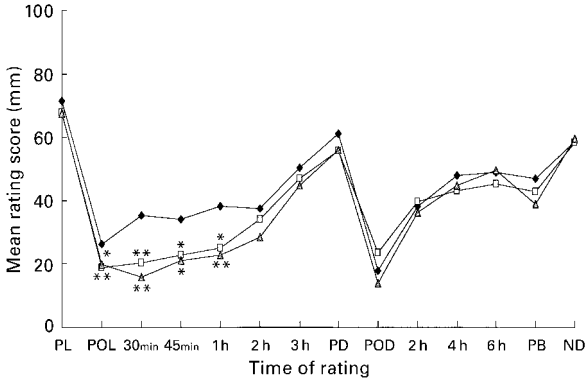

Fig. 1. Study 1. Diurnal profiles of subjective ratings of prospective consumption for subjects consuming lunch meals containing different test fats. (♦), Fat A, oleic blend; (▨), fat B, linoleic blend; (▲), fat C, stearic–oleic blend. Values are means for twenty subjects. Mean values were significantly different from those for fat A: * $P <$ 0·05, ** $P < 0{\cdot}01$. PL, pre-lunch; POL, post lunch; PD, pre dinner; POD, post dinner; PB, pre retiring to bed; ND, before breakfast the next day (day 2).

(F[2,36] 4·18, $P = 0·023$; A < B and C) but only during the 1 h period post lunch. Analysis of the same data from Study 2 did not reveal any main effects of lunch meal fat type.

(b) Post-dinner to pre-bed period. All ratings from both studies showed significant main effects of time as would be expected. Data from Study 1 did not reveal any further significant results. Data from Study 2, however, revealed significant lunch meal fat type × time interactions for ratings of hunger (F[9,162] 1·99, $P < 0·05$) and prospective consumption (F[9,162] 2·02, $P < 0·05$) and significant lunch meal fat type × sex interactions for ratings of prospective consumption (F[3,54] 5·61, $P < 0·01$) and desire to eat (F[3,54] 3·79, $P < 0·05$).

Inspection of the post-dinner profile of ratings of hunger and prospective consumption for the whole subject group (results not shown) revealed that on the days when the lunches containing fats A, C and D had been consumed, ratings rose during the evening to reach a peak at 4 h post-dinner before falling at the before-bed rating. In contrast, however, these rating scores did not fall after the 4 h rating (hence subjects were more hungry at the before-bed rating) when the lunch containing fat B had been consumed. Separate analyses of the rating data from males and females (results not shown) revealed significant main effects of lunch meal fat type on prospective consumption in females (F[3,27] 3·62, $P < 0·05$) but not in males, and on desire to eat in males (F[3,27] 3·04, $P < 0·05$) but not in females.

(c) Before-breakfast ratings on day 2. In both studies, the type of fat consumed in the test lunch meal on day 1 did not exert any effects on subjective ratings of hunger, desire to eat, fullness or prospective consumption made before breakfast on day 2.

End-of-day subjective ratings of hunger motivation and mood

In both studies, the fats consumed in the test lunch meal did not exert any differential effects on how anxious, contented, thirsty, hungry or full subjects rated themselves as feeling or on how often they had experienced strong urges to eat across the whole test day.

Energy and macronutrient intakes on day 2

The mean (n 20) energy and macronutrient intakes consumed on day 2 in both studies (assessed by food diary records) are shown in Table 4 along with the sum of the intakes on day 1 and day 2.

In Study 1 there was a tendency for energy and macronutrient intakes to be higher on day 2 when the lunch containing fat A had been consumed on day 1 than when the lunches containing fat B or fat C had been consumed on day 1. These effects were not, however, statistically significant. The four test fats administered in the lunch meals on day 1 in Study 2 did not exert any differential effects on energy or macronutrient intakes on day 2.

The sum of energy and macronutrient intakes on days 1 and 2

In Study 1, energy and macronutrient intakes summed

Table 4. Energy and macronutrient intakes of subjects on the day after (day 2) they had consumed a lunch meal containing a test fat (A, B, C or D)* and their combined intakes for the test day (day 1) and day 2

(Mean values with their standard errors for twenty subjects)

Test fat . . .	A		B		C		D	
Fat type . . .	Oleic		Linoleic		Stearic–oleic		Oleic–linoleic	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Study 1								
Day 2								
Energy (MJ)	9·5	0·7	8·7	0·7	8·6	0·4		
Fat (g)	89·9	8·8	85·7	10·3	80·9	6·2		
Protein (g)	83·9	9·0	70·5	5·8	75·7	4·2		
Carbohydrate (g)	299·2	24·6	273·5	18·1	274·0	16·1		
Day 1 + day 2								
Energy (MJ)	23·6	1·1	22·1	1·0	22·0	0·9		
Fat (g)	254·0	11·5	244·7	13·2	236·9	11·0		
Protein (g)†	196·8	13·3	175·6	10·1	182·5	9·4		
Carbohydrate (g)	680·6	37·6	635·2	27·3	638·2	26·4		
Study 2								
Day 2								
Energy (MJ)	7·9	0·8	8·2	0·5	8·6	0·7	8·6	0·7
Fat (g)	79·4	9·7	81·4	8·1	82·0	9·4	92·2	11·1
Protein (g)	71·0	6·7	72·5	5·2	72·7	6·9	78·5	7·3
Carbohydrate (g)	238·1	24·6	249·9	18·2	271·3	22·1	245·5	20·7
Day 1 + day 2								
Energy (MJ)	21·8	1·6	21·8	1·4	22·4	1·4	22·1	1·3
Fat (g)	246·1	19·2	240·4	18·1	243·0	17·0	249·1	18·4
Protein (g)	175·1	13·7	172·9	12·7	173·7	13·6	178·5	12·0
Carbohydrate (g)	613·2	49·1	625·7	41·3	657·8	42·6	617·1	35·1

* For details of test fats, see Table 1.
† Main effect of fat type, F[2,36] 3·32, $P < 0·05$.

Table 5. Combined values from studies 1 and 2 for energy and macronutrient intakes of subjects consuming lunch meals containing a test fat (A or B)† on day 1
(Mean values with their standard errors for forty subjects)

Test fat …	A Oleic								B Linoleic							
Fat type …	Energy (MJ)		Fat (g)		Protein (g)		Carbohydrate (g)		Energy (MJ)		Fat (g)		Protein (g)		Carbohydrate (g)	
Eating episode	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Dinner	3·8	0·3	42·0	3·9	40·9	3·2	97·6	7·7	3·4*	0·2	37·9	3·2	36·3**	2·7	87·7*	5·4
Evening snacks	3·4	0·4	41·7	4·7	22·0	3·0	94·2	10·2	3·3	0·4	39·4	4·9	20·8	2·9	94·6	11·0
Total day 1	14·0	0·6	165·4	7·5	108·5	5·5	378·2	18·2	13·5*	0·6	159·0*	7·3	102·8*	5·2	368·7	16·5
Day 2	8·7	0·5	84·6	6·5	77·5	5·6	268·7	17·8	8·5	0·4	83·5	6·5	71·5	3·8	261·7	12·8
Day 1 + day 2	22·7	1·0	250·1	11·1	186·0	9·6	646·9	31·0	22·0	0·9	242·5	11·1	174·2	8·1	630·4	24·4

Mean values were significantly different from those for test fat A: * $P < 0·05$, ** $P < 0·01$.
† For details of test fats, see Table 1.

across days 1 and 2 were higher when fat A had been consumed in the lunch on day 1 than when fats B and C had been consumed (see Table 4). This increased intake after fat A was, however, only significant for protein intake (F[2,36] 3·32, $P < 0·05$). No significant main effects of fat type were observed in Study 2.

Combined energy and macronutrient intake data from fat conditions A and B in both studies

The mean (n 40) energy and macronutrient intakes gained by combining the data from fat conditions A (oleic blend and B (linoleic blend) in both studies are shown in Table 5.

Dinner meal energy (F[1,38] 5·73, $P < 0·05$), protein (g) (F[1,38] 11·10, $P < 0·01$) and carbohydrate (g) (F[1,38] 4·74, $P < 0·05$) intakes were found to be significantly higher when subjects had consumed fat A in the lunch meal than when they had consumed the lunch containing fat B. Similarly total day 1 energy (F[1,38] 5·43, $P < 0·05$), fat (g) (F[1,38] 4·06, $P < 0·05$) and protein (g) (F[1,38] 13·32, $P < 0·01$) intakes were found to be significantly higher when subjects had consumed fat A in the lunch meal than when they had consumed the lunch containing fat B.

Discussion

The clearest result in Study 1 was the appetite-stimulating effect of fat A (or the appetite suppressing effects of fats B and C) as shown by both the intake data (see Tables 3 and 4) and the subjective ratings of motivation to eat (e.g. prospective consumption, Fig. 1). Since fats B and C produced very similar appetite responses it seems plausible that any appetite-stimulating effect of the oleic acid in fat C was counteracted by the presence of the stearic acid (or that any additional suppressive effect of fat C relative to fat B was blocked by a stimulating effect of the oleic acid). The results of Study 2, which was carried out in order to confirm and extend the findings of Study 1 (with the addition of an extra test fat condition, fat D, oleic–linoleic blend), were less clear (intake and rating data) but there was a tendency (non-significant) for fat A to stimulate appetite more than fat B.

The main difference in the findings of Study 1 and Study 2 was that the manufactured stearic–oleic fat blend (fat C in Study 2) produced somewhat differing post-ingestive effects to the naturally occurring stearic–oleic fat blend (fat C in Study 1). Hence in Study 2, consumption of fat C at lunch induced a total test day energy intake which was more-or-less equivalent to that when fat A had been consumed and higher than that when fat B had been consumed (see Table 3). Additionally, there was a non-significant tendency for carbohydrate intake (g) at dinner and over the whole test day to be higher after consumption of fat C than after consumption of fat B and even fat A (see Table 4). The inability of Study 2 to reproduce the appetite-suppressing effect of fat C observed in Study 1 may simply be due to the lower stearic acid content of fat C in Study 2 (see Table 1). Alternatively, it can be argued that the data from Study 2, where fat C induced similar effects on energy intake to fat A, are more in line with the results of oxidation studies carried out using labelled fats in both animals (e.g. Leyton *et al.* 1987) and human subjects (e.g. Jones *et al.* 1985).

The PUFA : SFA ratio of dietary fat has been reported to influence whole-body macronutrient oxidation (e.g. Jones & Schoeller, 1988). Oxidation studies indicate that dietary SFA are not oxidized as fuel sources as rapidly as PUFA and that they may favour fat deposition (Jones *et al*. 1992). Indeed, Shimomura *et al*. (1990) found that rats fed on a safflower-oil diet (high in PUFA) accumulated less body fat than rats fed on a beef-tallow diet (high in SFA). It has been argued that the degree of oxidative metabolism of free fatty acids (and glucose) in the liver constitutes a significant source of information useful for the control of appetite (Friedman *et al*. 1986; Friedman & Tordoff, 1986; Langhans & Scharrer, 1987; Stubbs *et al*. 1995*a*). The effect of dietary fat on food intake, therefore, depends on whether the fatty acids are oxidized or stored. The results of studies on fat fuel partitioning and food intake suggest that fat that is oxidized is satiating, whereas fat that is stored is not (Friedman, 1998).

The oleic–linoleic blend (fat D) used in Study 2 produced similar effects at dinner (day 1) to the oleic blend (fat A) with respect to energy, protein (g) and carbohydrate (g) intakes but similar effects to the linoleic blend (fat B) with respect to fat (g) intake. By the end of day 1, however, the effects of fat D were more similar to those of fat B with respect to energy, fat (g) and protein (g) intake. This suggests that the addition of linoleic acid to oleic acid (fat D) was able to block the appetite-stimulating effect of oleic acid.

The consistent difference between the effects of fats A and B in both studies prompted us to combine these two sets of data. Analysis carried out on the new data set confirmed the results of Study 1. Hence dinner meal energy intake after consumption of fat A was found to be significantly higher than that after fat B (n 40). Increasing the sample size (from n 20 to n 40) led to a corresponding increase in statistical power. For example, observed power for the main effects of fat type on the combined energy intake (from Studies 1 and 2) at dinner and over the whole of day 1 was between 0·6 and 0·7. Observed power for corresponding analysis of the separate data from Studies 1 and 2 was much lower (Study 1: dinner 0·419, total day 1 0·461; Study 2: dinner 0·310, total day 1 0·216). This lack of statistical power, therefore, explains why it was not possible to detect a significant main effect of fat type on energy intake at dinner in Study 1 or Study 2 or on energy intake over the whole of day 1 in Study 2.

The results of Studies 1 and 2 suggest that MUFA containing a high percentage of oleic acid may exert a relatively weak control over appetite compared with PUFA. Certainly, oleic acid is known to be the major storage fatty acid in human adipose tissue (Berry, 1994). MUFA, therefore, appear to engender fewer (or weaker) satiety signals than PUFA. An evaluation of the association between fat intake and adiposity, using data from the Quebec Family Study (Tremblay *et al*. 1998), indicates that whilst intakes of both MUFA and SFA seem to be good predictors of adiposity markers (e.g. body weight, BMI, skinfold thickness, waist circumference) a high intake of PUFA seems to exert no effect on these markers (Doucet *et al*. 1998). This study, therefore, supports the findings of Studies 1 and 2 with the respect to the effects of fats A and B and the findings of Study 2 with respect to the effect of fat C. These particular results are complemented by those of a recent study conducted by French *et al*. (1998) who investigated the effects of intestinal infusion of Intralipid and three oils, comprising predominantly stearic, oleic and linoleic acids, on food intake in lean male subjects. In this study, food intake was significantly suppressed by the Intralipid and linoleic fat infusions compared with saline whilst the oleic and stearic fat infusions had no significant effect on food intake. On balance, therefore, it appears that there is more evidence to support the effects of fat C in Study 2 rather than the effects of fat C in Study 1.

Taken together, the results of the two short-term studies reported here suggest that fats varying in degree of fatty acid saturation, but not fatty acid chain length, do appear to exert different effects on post-ingestive satiety, at least when large amounts of these fats are consumed. It is possible, however, that this may not be the case when smaller amounts of fatty acids are consumed in a mixture. Further work is therefore needed to address this issue. The required level of test fat consumption (83·2 g for all males and 58·3 g for all females) in the present studies resulted in average total daily fat intakes of between 156·0 and 166·7 g (see Table 3). This amounted to 44–45 % of total test day energy intake. This level of fat consumption corresponds to that consumed by the high fat consumers identified by both Blundell & MacDiarmid (1997) and Cooling *et al*. (1998) and is, therefore, ecologically valid.

Since the test fats were delivered in the same quantities in the different meals, and since the meals containing the test fats did not differ in weight, volume, visual appearance or oro-sensory qualities, the post-ingestive effects generated do appear to be due to the physiological effects of the fats after reaching the gastrointestinal tract. For a number of years the duodenal hormone CCK has been regarded as a physiological satiety signal. Interestingly, in human subjects, the Na salt of the MUFA oleic acid caused a greater release of CCK than did the SFA stearic acid (Beardshall *et al*. 1989). In the same study, maize oil (high in the diunsaturated fatty acid linoleic acid) produced a greater release of CCK than olive oil (high in oleic acid). These results suggest a role for CCK in mediating the effects of fats A and B in Studies 1 and 2 and possibly the effects of fat C in Study 2. Gastric emptying (which is known to be regulated by postprandially released CCK (e.g. Borovicka *et al*. 1996)) is another candidate mechanism.

Since the neurotransmitter 5-HT is known to influence satiety (Blundell, 1977, 1992) and is thought to alter nutrient preference (e.g. Wurtman, 1985) it would be expected that fats with differing effects on tryptophan uptake and 5-HT synthesis would influence one or both of these variables. Mullen & Martin (1992) found that a 340 g/kg tallow diet (high in SFA) increased rat serum insulin and brain 5-HT levels (leading to dietary carbohydrate avoidance) whereas a 340 g/kg maize oil (lower saturation) diet had no effect (leading to carbohydrate preference). This suggests that differential effects of degree of fatty acid saturation on 5-HT synthesis may have been involved in mediating the results of the present studies. Since there is now evidence to suggest that 5-HT and CCK mechanisms partially interact to bring about a suppression of food intake (Stallone *et al*. 1989; Cooper *et al*. 1990) it is likely that both were involved.

Overall, the results of the present studies indicate that PUFA may exert a stronger control over appetite than

MUFA and SFA. The health benefits of consuming a diet high in MUFA (with respect to prevention of atherosclerosis) are well documented and it is not our intention to discourage consumption of such a diet. The results presented here, however, do suggest a role for inclusion of PUFA in food products as a means of enhancing satiety. There now exists an urgent need for a long-term trial to investigate the effects of different fats on appetite control in free-living subjects.

Acknowledgements

These studies were carried out as part of the MAFF AGRO FOOD LINK PROJECT (LINK AFQ 26M); a collaboration between The University of Leeds, The Ministry of Agriculture, Fisheries and Food and a consortium of industrial partners (Cadbury (UK) Ltd, Nestlé Ltd, The Sugar Bureau, Unilever Research Laboratories, United Biscuits (UK) Ltd.). The test fats and certain foods used in these studies were provided by Unilever Research Laboratories and Cadbury (UK) Ltd.

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Appendix

Table 1. Nutritional composition (per 100 g) of foods provided to subjects at a dinner meal, together with the amounts of the excess portions provided (in parentheses)

Food item	Energy (kJ)	Fat (g)	Protein (g)	Carbohydrate (g)
Medium-cut wholemeal bread (7 slices)	908	2·6	9·0	41·9
Butter (85 g)	3084	81·7	0·5	0·0
Lean turkey breast (150 g)	385	0·6	20·3	1·5
Grated cheddar cheese (100 g)	1724	34·4	25·5	0·1
Iceberg lettuce (40 g)	54	0·3	0·7	1·9
Tomato (100 g)	71	0·3	0·7	3·1
Cucumber (50 g)	38	0·1	0·7	1·5
Branston pickle (1 jar)	561	0·2	0·7	34·5
Heinz salad cream (1 bottle)	1431	27·8	1·4	22·9
Ready-salted potato crisps (50 g)	2247	36·8	6·5	47·9
Strawberry yoghurt (2 pots)	351	0·7	5·4	15·0
Crème caramel (2 pots)	423	1·2	3·4	20·5
Fruit salad in fruit juice (450 g)	155	0·0	0·0	9·9
Apple, cored and sliced (2)	146	0·0	0·2	9·2
Water (large jug)	–	–	–	–

Table 2. Nutritional composition (per portion) of foods provided to subjects in a snack box, together with the actual amounts provided

Food item	Energy (kJ)	Fat (g)	Protein (g)	Carbohydrate (g)
Wholemeal bread rolls (per roll, six provided)	213	0·8	2·4	9·0
White bread rolls (per roll, six provided)	314	0·9	2·9	14·7
Flora margarine (per 10 g portion, four provided)	305	8·0	0·02	0·13
Strawberry jam (per 20 g portion, four provided)	218	0·0	0·12	13·8
Cheese (per 20 g portion, four provided)	343	6·9	5·1	0·0
Fruit yoghurt (per pot, two provided)	531	1·7	3·8	25·8
Ready-salted crisps (per packet, two provided)	657	12·0	1·9	11·0
Chocolate biscuits (per packet, two provided)	615	7·3	1·9	19·7