

High-fat diet-induced obesity in animal models

Niloofar Hariri and Louise Thibault*

School of Dietetics and Human Nutrition, McGill University, Quebec, Canada

Epidemiological studies have shown a positive relationship between dietary fat intake and obesity. Since rats and mice show a similar relationship, they are considered an appropriate model for studying dietary obesity. The present paper describes the history of using high-fat diets to induce obesity in animals, aims to clarify the consequences of changing the amount and type of dietary fats on weight gain, body composition and adipose tissue cellularity, and explores the contribution of genetics and sex, as well as the biochemical basis and the roles of hormones such as leptin, insulin and ghrelin in animal models of dietary obesity. The major factors that contribute to dietary obesity – hyperphagia, energy density and post-ingestive effects of the dietary fat – are discussed. Other factors that affect dietary obesity including feeding rhythmicity, social factors and stress are highlighted. Finally, we comment on the reversibility of high-fat diet-induced obesity.

Dietary obesity: Rats: Mice: High-fat diet

Introduction

Obesity is considered to be a major risk factor for chronic diseases such as CHD and hypertension, type 2 diabetes, and some types of cancer⁽¹⁾. Its prevalence is increasing, with 400 million obese and 1.6 billion overweight adults around the world⁽¹⁾. Although genetics plays a role in the regulation of body weight, body size and body composition and the metabolic response to feeding in humans^(2–6) and in animals^(7,8), the increase in worldwide obesity in a short period of time cannot be explained by genetics; there are individual differences in genetic susceptibility to environmental factors such as diet^(2,6,9–11).

Dietary fat intake often has been claimed as responsible for the increase in adiposity. Human studies have shown that high-fat diets ($\geq 30\%$ of energy from fat) can easily induce obesity^(10,12–15). Epidemiological studies conducted in countries such as China, Canada and the USA have shown that, when the average amount of fat in the diet increases, the incidence of obesity also increases^(16–19). This has led to a worldwide effort to decrease the amount of fat in the human diet.

Diets rich in fat not only induce obesity in humans but also make animals obese^(20–22). In both rats^(23,24) and mice^(25,26) a positive relationship has been found between the level of fat in the diet and body weight or fat gain. In the scientific literature it was first shown that rats consuming diets containing high proportions of fat gained weight faster than those on diets containing minimal amounts of fat^(27,28).

In 1949, obesity was induced for the first time in rats by *ad libitum* feeding of a semi-liquid palatable diet⁽²⁹⁾. Then in 1953, Fenton & Dowling used high-fat diets with fat at 50% of total energy in weanling mice to induce obesity; they called it nutritional obesity⁽³⁰⁾ but the model was later renamed as dietary obesity⁽³¹⁾.

Since under-reporting is an important bias in epidemiological studies on diet and obesity in human subjects^(32–34), animal models have been widely utilised for experiments on dietary obesity^(7,8,35,36). Usually high-fat diets within the range of 30–78% of total energy intake are used⁽²¹⁾ – either by adding a particular fat to the animal's diet or using an assortment of fat- and sugar-rich supermarket foods (cafeteria diet) – for studying obesity in rats^(24,37–46) and mice^(25,47–52). The use of high-carbohydrate–low-fat diets has not been found as efficient as high-fat–low-carbohydrate diets in inducing obesity^(24,41,53).

It has been reported that despite the growing problem of obesity, Canadians and Americans are eating less fat than a generation ago^(54,55). This shows that the increasing rate of obesity cannot be totally explained by high intakes of fat in the diet, suggesting that the type of fat may also play a role, although the results of the studies in human subjects and animals have not been conclusive⁽⁵⁶⁾. Some studies have reported that not all fats are obesogenic and the dietary fatty acid profile rather than the amount of energy from fat is an important variable in developing dietary obesity^(25,47,57–60), but there is some controversy on this matter since there are

Abbreviation: ICV, intracerebroventricular.

* **Corresponding author:** Dr Louise Thibault, fax +1 514 398 7739, email louise.thibault@mcgill.ca

reports showing non-significant differences in final body weight and/or body-weight gain of the animals consuming various fatty acids^(53,61–66).

Other factors that may contribute to obesity induced by a diet rich in fat include failure to adjust oxidation of fat to the extra fat in the diet⁽¹⁵⁾, increase in adipose tissue lipoprotein lipase activity⁽⁶⁷⁾, increased meal size and decreased meal frequency⁽⁶⁸⁾, as well as overconsumption of energy attributed to high energy density of the diet^(69–72), orosensory characteristics of fats and poorly satiating properties of the high-fat diets^(22,69,70). Reviews of dietary obesity describe potential mechanisms of body weight and food intake regulation involving the central nervous system – mainly the hypothalamus – neuropeptides such as ghrelin and neuropeptide Y, and hormones such as insulin and leptin^(73,74). Adipose tissue *per se* is considered to be an endocrine organ that secretes cytokines such as IL-6 and TNF α ; thus obesity could possibly be regarded as a chronic inflammatory disease^(73–76).

Obesity occurs when energy uptake surpasses energy expenditure in the individual animal and so the stores of energy in body fat are enlarged, particularly in adipose tissues. Obesity involves both or either an increase in the number of adipocytes (hyperplasia) and their size (hypertrophy)^(10,77,78). Initially it was hypothesised that adipocyte number was determined in early childhood and that the obesity developed during adulthood was a result of an increase in adipocyte size^(79,80). However, it is now known that hyperplasia is an ongoing event not limited to childhood. At any stage of life when adipocytes enlarge to the point of hypertrophy, they release factors such as TNF α and insulin-like growth factor that stimulate hyperplasia of the adipocytes^(76,77,81). Conversely, recent studies on reversal of obesity in human subjects have found decreases not only in the size of the fat cells but also in their number: the loss of weight is followed by apoptosis of adipocytes^(78,81).

This paper summarises the present literature on factors that can play a role in the development of obesity and explores mechanisms that have been proposed for obesity induced by a diet rich in fat. The adequacy of the paradigm of high-fat diets in animal models of human obesity will be discussed. The possibility of reversing dietary obesity in animal models will be explored. Physical activity is another important factor in obesity; however, the present paper focuses on dietary factors only. Some reviews have been published about diverse areas of dietary obesity that have been cited in this introduction but the aim of the present review is to summarise the range of relevant results and to provide a conclusive coverage of the different aspects of obesity from high-fat diets in non-human species.

Assessment of dietary obesity

In animal models, as in humans, obesity can be assessed by criteria based on (1) gain of body weight or the Lee obesity index and/or (2) increase of body fat content. However, standard thresholds for obesity have not been developed like BMI in human beings. In most studies, the degree of obesity has been evaluated by comparing body weight (or fat) of the

experimental group fed a high-fat or energy-dense diet with control animals that show normal growth while fed chow or low-fat diets^(20,24,41,42,45,82). Researchers that have attempted to do so differed in the values that are 10–25 % greater body weight than age-matched control rats fed chow (normal pattern of body-weight gain) as moderate obesity^(41,42) and greater than 40 % as severe obesity⁽⁸²⁾.

The Lee index for assessing obesity in rats is similar to BMI in humans. It was defined by Lee in 1929⁽⁸³⁾ as the cube root of body weight (g) divided by the naso–anal length (cm) and multiplied by 1000. Lee considered values greater than 310 as an indicator of obesity. Since then some researchers have used the Lee index to assess the levels of obesity in rats^(44,84–88). Reliable correlations were found in some studies between the Lee index and fat content of the body^(86,89–91).

In human subjects body composition assessment with methods such as air displacement plethysmography or dual-energy X-ray absorptiometry gives a more precise idea of the degree of obesity than do anthropometric measurements alone^(92,93). For example, children and adolescent males have smaller fat mass than females of a similar BMI, and this difference is more pronounced in the older age group; and so the relationship between BMI and the direct measures of adiposity is influenced by factors such as sex and age⁽⁹²⁾. Dual-energy X-ray absorptiometry is also used in rats for assessing body composition^(24,94). In rats fed diets high in fat, a linear increase in body fat with increasing body weight has been shown^(25,45). However, results of the study of Woods *et al.*⁽⁴²⁾ showed that measuring body fat is a more sensitive criterion for assessing obesity in animals, since rats fed a high-fat diet (40 % of energy) for 10 weeks displayed a 10 % increase in total body weight but a 35–40 % increase in total body fat compared with the animals fed a low-fat diet.

In models of dietary obesity, animals are classified as prone and resistant based on their body weight, body-weight gain, body fat, or noradrenaline concentrations in urine. Tulipano *et al.*⁽⁹⁵⁾ categorised Sprague–Dawley rats fed a high-fat diet based on their final body weight, with rats in the highest quartile designated as obesity prone and those in the lowest quartile assigned as obesity resistant. In some studies upper (prone) and lower (resistant) tertiles of body-weight gain^(46,51,96) or body fat⁽⁹⁷⁾ of the animals fed high-fat diets have been used for this classification. Before developing obesity while fed with chow, prone and resistant animals have also been identified based on high and low levels of urinary noradrenaline, respectively^(98,99).

High-fat diets

Energy density

In humans, a significant positive relationship has been found between the amount of dietary energy from fat and the proportion of the population who are overweight (in epidemiological studies), and in clinical studies between the level of dietary fat and body-weight gain as well as between the reduction in the dietary fat and weight loss^(16,17,19,100). These associations have also been shown in animal studies^(23–26,101). This relationship in humans or in animal

models of more dietary fat leading to greater obesity shows that the fat content of the diet is an important factor in energy balance. In general, diets containing more than 30 % of total energy as fat lead to the development of obesity.

Researchers have induced obesity by diets having different percentages and sources of fats in rats^(24,31,37–45,53,82,102–105), mice^(25,47–52,60) and hamsters⁽¹⁰⁶⁾. Furthermore, the characteristics of the diets used have differed within and between laboratories in macronutrient composition, energy density and orosensory properties. In many animal studies the composition of the control diet was not shown or a non-purified chow control diet was used. This could have confounding effects arising from comparisons made with the high-fat diets.

Since the original observations of dietary obesity, obesity has been induced in animals by diets containing fat as low as 13 % of total energy in a high-energy diet⁽⁴¹⁾ (Table 1; line 26) (which is more than the rat's requirement for fat: 5 %) to as high as 85 % of energy⁽³⁷⁾ (Table 1; line 1). Several researchers have reviewed the amount of fat required to induce obesity in animals. The most recent review was by Buettner *et al.*⁽²¹⁾ who summarised studies conducted between 1997 and 2007, and concluded that the best method to induce obesity in animals was to use semi-purified high-fat diets containing animal fats at 40 % of energy, with a low amount of *n*-3 fatty acids and a low amount of plant oils rich in *n*-6 and *n*-9 fatty acids.

Interestingly, some recent studies have indicated that the development of obesity is prevented in humans and rats when the increase in dietary fat is accompanied by an increase in protein (high protein:carbohydrate and low carbohydrate:fat ratios)^(107–109). This has been related to greater satiety with high-protein diets, lower insulin levels with low-carbohydrate diets and the energy required to convert amino acids in glucose compounds for gluconeogenesis⁽¹⁰⁷⁾. High-protein diets were also found to increase cholecystokinin and decrease plasma levels of the orexigenic hormone ghrelin^(110,111), reduce gastric emptying⁽¹¹¹⁾ and increase central nervous system leptin sensitivity^(109,112). Moreover, high-protein diets resulted in a decrease in fatty acid synthase enzyme activity in the liver that reduces hepatic lipogenesis⁽¹⁰⁷⁾. The increase in circulating amino acids *per se* is a satiety signal and inhibits food intake through suppressing the gene expression of agouti-related protein (a neuropeptide in the brain that increases appetite)^(110,113). However, Huang *et al.*⁽¹¹⁴⁾ showed that increasing the dietary protein:carbohydrate ratio could not reduce the degree of obesity when obesity had already been induced in high-fat diet-fed mice (at 40 % of energy). Therefore they suggested that these diets might be efficient in preventing obesity but may not reverse obesity once established.

In the human diet, an increase in dietary fat is usually accompanied by a decrease in carbohydrate while the protein is relatively constant (for example, fat 35–45 %, carbohydrate 45–55 %, protein 15–20 %). This is why a presumably positive relationship between the level of fat of the diet and degree of obesity is usually found in epidemiological studies without controlling for dietary protein level.

Dietary profile of fatty acids

Fatty acid composition of the diet may play an important role in body-weight regulation and cellularity of adipose tissue (fat cell volume and number)^(56,59,115,116). Studies in human subjects have shown that SFA are more obesogenic than PUFA^(57,58,117–119). This idea has been supported by animal studies by showing either greater accumulation of body fat^(43,47,120–122) (Table 1; lines 19, 21, 16, 18 and 37, respectively) or higher body weight^(25,47,60,122) (Table 1; lines 11, 21, 33 and 18, respectively) on feeding with diets moderate or rich in SFA. A study conducted by Ellis *et al.*⁽⁵³⁾ in 3-week-old female Sprague–Dawley rats comparing diets rich in low-SFA maize oil or high-SFA coconut oil (40 % of total energy) for 8 weeks found higher fat cell number in animals fed coconut oil and greater fat cell size in the rats fed maize oil. Since hypertrophy of adipocytes is a prerequisite for hyperplasia, those results show that more severe form of obesity developed from feeding a diet high in SFA.

The obesogenic effect of SFA can be explained by the fact that SFA are poorly used for energy, and so remain to be acylated into TAG and stored in adipose tissue, whereas PUFA and MUFA are readily used for energy and so stored less⁽⁵⁹⁾. In other words, the effective energy content of a diet is greater when the fats in it are high in SFA. In addition, the rate of oxidation of SFA decreases with increase of carbon chain length⁽⁵⁷⁾. Furthermore, unlike MUFA and PUFA, SFA decrease RMR and diet-induced thermogenesis^(116,118,123–125). Moussavi *et al.*⁽⁵⁶⁾ suggested that PUFA suppress the expression of lipogenic transcription genes while MUFA and SFA do not.

Another possible mechanism is that saturation of fatty acids decreases their suppressive effect on dietary intake: thus fats and oils containing high proportions of linoleic acid are more satiating than fats and oils rich in oleic or stearic acid^(13,117,126). PUFA inhibit appetite more strongly than MUFA or SFA through an increase in the release of cholecystokinin which augments other signals of satiety^(117,126). Another study, however, failed to confirm that SFA induced less satiety than MUFA⁽¹²⁷⁾.

A study in adult male Wistar rats showed that feeding high-fat diets (60 % of energy) for 8 weeks resulted in greater intrathoracic fat mass in animals fed a SFA-rich diet (cocoa butter) and greater intra-abdominal and epididymal fat mass in those fed PUFA (safflower-seed oil)⁽⁶¹⁾ (Table 1; line 38). There are also reports of studies that did not show any specific effect of SFA and PUFA on body weight or fat mass^(64,128) (Table 1; lines 17 and 25, respectively).

Short-chain (C2:0–C4:0) and medium-chain (C6:0–C12:0) fatty acids are directly transported to the liver via the portal system, are not dependent upon carnitine for entering the mitochondria and therefore are oxidised more and deposited less in adipose tissue than long-chain fatty acids (C14:0–C24:0)^(56,129,130). Short-chain and medium-chain fatty acids also increase diet-induced thermogenesis and energy expenditure^(56,130). The lower obesogenic effect of medium-chain TAG, which are composed of medium-chain fatty acids, was shown in many studies. Isoenergetic diets (with fat at 12 % of total energy) containing olive oil or medium-chain fatty acid (octanoic acid) offered for 23 d to

Table 1. Studies of high-fat diet-induced obesity (DIO) in animal models

| Reference | Species, strain, sex, weight, age | DIO diet | Diet composition | | | Changes in body weight and dietary intake | | | | | | | | Line no. |
|--|--|---|------------------|-------------------|--|---|-------------------|------------------|-----------------------------|----------------------|-----------------------------|-----------------|---------------|----------|
| | | | Amount of fat | | Control diet | Amount of fat | | Duration (weeks) | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | | | | | | |
| Mickelsen <i>et al.</i> (1955) ⁽³⁷⁾ | Rats, Osborne–Mendel, male, 300 g, adult | g/100 g | | | g/100 g | | | | | | | | | |
| | | 60 Crisco® (Proctor & Gamble, Cincinnati, OH, USA) 25 casein 7 sucrose 1 starch 4 mineral salts 3 cottonseed oil containing: 2 vitamin A and D 1 vitamin E | 63 | 85 | 30 casein 61 sucrose 2 starch 4 mineral salts 3 cottonseed oil containing: 2 vitamin A and D 1 vitamin E | 3 | 7 | 41 | i | nr | – | – | – | 1 |
| Schemmel <i>et al.</i> (1969) ⁽⁴⁵⁾ | Rats, Osborne–Mendel, male and female, 57.5 ± 6.4 g (female), 51.6 ± 3.1 g (male), 3–5 weeks | g/100 g | | | | | | | | | Total | | | |
| | | 60 Crisco® 25 casein liver 2 liver powder 0.25 DL-methionine 5 mineral mix 2.2 vitamin mix 0.01 auremycin 2 fibre | 60 | 78 | Grain | nr | nr | 65 | i | nr | i | – | – | 2 |
| Herberg <i>et al.</i> (1974) ⁽⁴⁹⁾ | Mice, NMRI, male, 19.2 ± 0.2 g (DIO diet), 19.3 ± 0.2 g (control diet), 4 weeks | g/100 g | | | g/100 g | | | | | | Epididymal and subcutaneous | | kcal | |
| | | 38 soya oil 24 casein 10 starch 16 sucrose 5 powdered cellulose 1 vitamin mix 6 mineral mix | 38 | 63 | 20 protein 30 oatmeal 24 whole meal 13 flour 7 wheat 2.2 sweet whey 2.5 distillers solubles 0.2 vitamin mix 1.1 mineral mix % of total energy | 6.2 | 13 | 11–12 | i | i | i | d | 0 | 3 |
| Lemonnier <i>et al.</i> (1975) ⁽⁵⁰⁾ | Mice, Swiss, male and female, nr, weaning | g/100 g | | | | | | | | | Genital | | | |
| | | 53 lard % of energy 72 lipid 22 protein 6 carbohydrate | 53 | 72 | 9 lipid 22 protein 69 carbohydrate | 4.5 | 9 | | i | nr | i | – | – | 4 |
| Sclafani & Springer (1976) ⁽²²⁸⁾ | Rats, CFE, female, 234–239 g, 17 weeks | g/100 g | | | | | | | | | | | | |
| | | 33 Crisco® 67 Purina chow + sweetened condensed milk + palatable super-market foods: chocolate chip cookies, salami, banana, marshmallows, milk chocolate, peanut butter | >33 | >52.5 | Purina chow (company not specified) | 4.5 | 9.6 | 8–9 | nr | i | – | – | – | 5 |

Table 1. Continued

| Reference | Species, strain, sex, weight, age | Diet composition | | | | | | | Changes in body weight and dietary intake | | | | | | Line no. |
|--|--|---|-----------------------------------|---|--|---------------|--|------------------|---|----------------------|---|-----------------|---------------|----|----------|
| | | DIO diet | Amount of fat | | Control diet | Amount of fat | | Duration (weeks) | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | | | | | | | |
| Sclafani & Gorman (1977) ⁽⁴⁴⁾ | Rats, CFE, male and female, 308 g and 12 weeks (male), 233 g and 13 weeks (female) | Purina chow + supermarket foods: marshmallows, cheese puffs, sugar-coated cereal, chocolate cookies, peanut butter, bologna, sweetened condensed milk g/100 g | nr | nr | Purina chow (company not specified) | 4.5 | 9.6 | 8.5 | nr | i | – | – | – | 6 | |
| Faust <i>et al.</i> (1978) ⁽¹⁰³⁾ | Rats, Sprague–Dawley and Osborne–Mendel, male, nr, 17 weeks | 55 Crisco [®] 25 casein 13 dextrose 4 mineral salts 2.82 vitamin mix 0.12 L-cystine 0.06 L-cysteine g/100 g | 55 | 76 | Purina chow (company not specified) | 4.5 | 9.6 | 8.5 | i (both strains) | nr | Retroperitoneal and gonadal i (both strains) | – | – | 7 | |
| | | Oscari (1982) ⁽³⁸⁾ | Rats, Wistar, female, nr, weaning | 4.84 maize oil 18.16 lard 18 casein 49.5 sucrose 2 brewer's yeast 2 liver powder 4 Hegsted salt mixture 1.5 vitamin mix g/100 g | 23 | 42 | Purina chow (Ralston Purina, Nestlé Purina PetCare, St Louis, MO, USA) | 4.5 | 9.6 | 58 | i | nr | i | nr | – |
| Wade (1982) ⁽¹⁰⁶⁾ | Hamsters, golden, male and female, 80–110 g, nr | Two parts Purina chow (Purina Rodent Chow, no. 5001) One part vegetable shortening (company not specified) g/100 g | >33 | >52.5 | Purina chow (Purina Rodent Chow, no. 5001) | 4.5 | 9.6 | 4 | nr | i | Total | | kcal | | |
| Bourgeois <i>et al.</i> (1983) ⁽²⁵⁾ | Mice, NMRI, male and female, nr, 4 weeks | 78.5 wheat flour 12.1 casein 3 bran 0.4 DL-methionine 2.1 vitamin mix 3.9 mineral mix g/100 g | 5 | 6.9 | | 3 | 6.1 | 13 | 0 | nr | Retroperitoneal and parametrial 0 | – | – | 10 | |
| | | 5 lard 3.2 bran 0.3 DL-methionine 4.3 mineral mix 2.4 vitamin mix 14 casein 70.8 wheat flour 10 lard 3.5 bran 0.2 DL-methionine 4.6 mineral mix 2.5 vitamin mix 17 casein 62 wheat flour 20 lard 3.9 bran 0.1 DL-methionine 5.2 mineral mix 2.9 vitamin mix 21.9 casein 45.5 wheat flour g/100 g | 10 | 26.8 | | | | i (female only) | nr | 0 | – | – | | | |
| | | | 20 | 43.5 | | | | i | nr | i | – | – | | | |

| | | | | | | | | | | | | | | |
|--|--|--|------|------|--|-----|-----|----|---|---|---|----|---|----|
| Bourgeois <i>et al.</i> (1983) ⁽²⁵⁾ | Mice, NMRI, male and female, nr, 4 weeks | 30 lard 4.2 bran 0.05 DL-methionine 5.6 mineral mix 3.1 vitamin mix 27 casein 30.1 wheat flour g/100 g | 30 | 55.9 | | | | | i | nr | i | – | – | |
| | | 30 lard 4.2 bran 0.05 DL-methionine 5.6 mineral mix 3.1 vitamin mix 27 casein 30.1 wheat flour g/100 g | 30 | 55.9 | 78.5 wheat flour 12.1 casein 3 bran 0.4 DL-methionine 2.1 vitamin mix 3.9 mineral mix | 3 | 6.1 | 13 | i | nr | i v. beef tallow (male only) d v. beef tallow (female only) | – | – | 11 |
| | | 30 lard 4.2 bran 0.05 DL-methionine 5.6 mineral mix 3.1 vitamin mix 27 casein 30.1 wheat flour | 30 | 55.9 | | | | | i i v. sunflower-seed oil (female only) | nr | i d v. lard, soya-bean oil (male only) i v. lard, soya-bean oil, sunflower-seed oil (female only) | – | – | |
| | | 30 soyabean oil 4.2 bran 0.05 DL-methionine 5.6 mineral mix 3.1 vitamin mix 27 casein 30.1 wheat flour g/100 g | 30 | 55.9 | | | | | i | nr | i i v. beef tallow (male only) d v. beef tallow (female only) | – | – | |
| Cunnane <i>et al.</i> (1986) ⁽⁴⁸⁾ | Mice, ob/ob and in/in, male, 22 g (in/in), 36 g (ob/ob), 6 weeks | 30 sunflower-seed oil 4.2 bran 0.05 DL-methionine 5.6 mineral mix 3.1 vitamin mix 27 casein 30.1 wheat flour g/100 g | 30 | 55.9 | | | | | i d v. beef tallow (female only) | nr | i i v. beef tallow (male only) | – | – | |
| | | 10 evening primrose oil 20 casein 60 sucrose 5.5 cellulose 3.5 mineral mix 1 vitamin mix 10 cod liver oil 20 casein 60 sucrose 5.5 cellulose 3.5 mineral mix 1 vitamin mix g/100 g | 10 | 21 | Purina chow (Jackson laboratory, no. 5001) | 4.5 | 9.6 | 16 | 0 i v. cod liver oil (ob/ob only) | 0 d v. cod liver oil (in/in only) | 0 v. cod liver oil | 0 | – | 12 |
| | | | | | | | | | 0 d v. evening primrose oil (ob/ob only) | 0 d v. evening primrose oil (in/in only) | 0 v. evening primrose oil | 0 | – | |
| | | | | | | | | | | | | | | |
| Chang <i>et al.</i> (1990) ⁽⁴⁰⁾ | Rats, Wistar, female, nr, nr | 32.70 maize oil 29.20 casein 12.20 sucrose 12.15 dextrin 6.30 solka floc 2 vitamin mix 5 mineral mix 0.30 DL-methionine 0.15 choline chloride g/100 g | 32 | 60 | 8.2 maize oil 22 casein 29.35 sucrose 28 dextrin 6.30 Solkafloc 2 vitamin mix 5 mineral mix 0.20 DL-methionine 0.15 choline chloride | 8.2 | 20 | 5 | 0 (obesity resistant only) i (obesity prone only) i (obesity prone v. obesity resistant) | i (obesity prone v. obesity resistant) | i (obesity prone v. obesity resistant) | nr | i (obesity prone v. obesity resistant) | 13 |
| | | | | | | | | | | | | | | |
| Su & Jones (1993) ⁽⁶⁶⁾ | Rats, Sprague–Dawley, male, 65–85 g, nr | 22.4 fish oil 27.8 maize starch 11.2 sucrose 22.4 casein 6.19 cellulose 1.24 vitamin mix 8.65 mineral mix | 22.4 | 42 | nr | nr | nr | 12 | 0 v. other DIO diets | 0 v. other DIO diets | d v. beef tallow and olive oil 0 v. other DIO diets | nr | 14 | |
| | | | | | | | | | | | | | | |

Table 1. Continued

| Reference | Species, strain, sex, weight, age | Diet composition | | | | | | Changes in body weight and dietary intake | | | | | | Line no. |
|--|---|--|--|-------------------|-------------------------------------|---------------|----------------------|---|-----------------------------|----------------------|----------------------|--------------------------|----------------------|----------|
| | | DIO diet | Amount of fat | | Control diet | Amount of fat | | Duration (weeks) | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | | | | | | |
| Hill <i>et al.</i> (1993) ⁽⁶³⁾ | Rats, Wistar, male, 300 g, 13–17 weeks | 22-4 safflower-seed oil | 22-4 | 42 | | | | | 0 v. other DIO diets | 0 v. other DIO diets | 0 v. other groups | 0 v. other DIO diets | nr | |
| | | 27-8 maize starch | | | | | | | | | | | | |
| | | 11-2 sucrose | | | | | | | | | | | | |
| | | 22-4 casein | | | | | | | | | | | | |
| | | 6-19 cellulose | | | | | | | | | | | | |
| | | 1-24 vitamin mix | | | | | | | | | | | | |
| | | 8-65 mineral mix | | | | | | | | | | | | |
| | | 22-4 olive oil | 22-4 | 42 | | | | | 0 v. other DIO diets | 0 v. other DIO diets | i v. fish oil | 0 v. other DIO diets | nr | |
| | | 27-8 maize starch | | | | | | | | | | | | |
| | | 11-2 sucrose | | | | | | | | | | | | |
| | | 22-4 casein | | | | | | | | | | | | |
| | | 6-19 cellulose | | | | | | | | | | | | |
| | | 1-24 vitamin mix | | | | | | | | | | | | |
| | | 8-65 mineral mix | | | | | | | | | | | | |
| | | 22-4 beef tallow | 22-4 | 42 | | | | | 0 v. other DIO diets | 0 v. other DIO diets | i v. fish oil | 0 v. other DIO diets | nr | |
| | | Shillabeer & Lau (1994) ⁽¹²⁰⁾ | Rats, Sprague–Dawley, male, 50–60 g, 4 weeks | 27-8 maize starch | | | | | | | | | | |
| 11-2 sucrose | | | | | | | | | | | | | | |
| 22-4 casein | | | | | | | | | | | | | | |
| 6-19 cellulose | | | | | | | | | | | | | | |
| 1-24 vitamin mix | | | | | | | | | | | | | | |
| 8-65 mineral mix | | | | | | | | | | | | | | |
| g/100 g | | | | | | | | | | | Total | | kcal | |
| 18-2 maize oil | 19-5 | | | 45 | nr | nr | nr | 25 | 0 v. other DIO diets | nr | i v. fish oil | – | 0 v. other DIO diets | 15 |
| 1-3 safflower-seed oil | | | | | | | | | | | | | | |
| 20 casein | | | | | | | | | | | | | | |
| 16-2 sucrose | | | | | | | | | | | | | | |
| 16-2 maize starch | | | | | | | | | | | | | | |
| 0-3 DL-methionine | | | | | | | | | | | | | | |
| 5 fibre | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | |
| 3-5 mineral mix | | | | | | | | | | | | | | |
| Jones <i>et al.</i> (1995) ⁽⁶⁴⁾ | Rats, Sprague–Dawley, male, 193 ± 9-1 g, nr | 18-2 lard | 19-5 | 45 | | | | | 0 v. other DIO diets | nr | i v. fish oil | – | i v. fish oil | |
| | | 1-3 safflower-seed oil | | | | | | | | | | | | |
| | | 20 casein | | | | | | | | | | | | |
| | | 16-2 sucrose | | | | | | | | | | | | |
| | | 16-2 maize starch | | | | | | | | | | | | |
| | | 0-3 DL-methionine | | | | | | | | | | | | |
| | | 5 fibre | | | | | | | | | | | | |
| | | 1 vitamin mix | | | | | | | | | | | | |
| | | 3-5 mineral mix | | | | | | | | | | | | |
| | | % of total energy | | | | | | | | | | Epididymal, and inguinal | | kcal |
| | | 59 beef tallow | 38 | 45 | Purina chow (company not specified) | 4-5 | 9-6 | 26 | 0 | nr | i | nr | 0 v. other DIO diets | 16 |
| | | 21 carbohydrate | | | | | | | 0 v. other DIO diets | | 0 v. other DIO diets | | | |
| | | 20 protein | | | | | | | | | | | | |
| | | 59 safflower-seed oil | 38 | 45 | | | | | 0 | nr | 0 | nr | 0 v. other DIO diets | |
| | | 21 carbohydrate | | | | | | | 0 v. other DIO diets | | 0 v. other DIO diets | | | |
| | | 20 protein | | | | | | | | | | | | |
| 5 beef tallow | 2-2 | 5 | | | | | 0 | nr | 0 | nr | 0 v. other DIO diets | | | |
| 75 carbohydrate | | | | | | | 0 v. other DIO diets | | 0 v. other DIO diets | | | | | |
| 20 protein | | | | | | | | | | | | | | |
| g/100 g | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|--|----------------------------------|----|------|---------|----|----|----|--|----|------------|----|----------------------|----|
| Takeuchi <i>et al.</i> (1995) ⁽¹²²⁾ | Rats, Sprague– Dawley, male, 95–97 g, 4 weeks | 19 beef tallow | 20 | 40 | nr | nr | nr | 10 | 0 v. other DIO diets | nr | – | – | nr | 17 |
| | | 31.2 maize starch | | | | | | | | | | | | |
| | | 11.2 sucrose | | | | | | | | | | | | |
| | | 22.4 casein | | | | | | | | | | | | |
| | | 6.2 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 8.6 mineral mix | | | | | | | | | | | | |
| | | 19 fish oil | 20 | 40 | | | | | 0 v. other DIO diets | nr | – | – | nr | |
| | | 31.2 maize starch | | | | | | | | | | | | |
| | | 11.2 sucrose | | | | | | | | | | | | |
| | | 22.4 casein | | | | | | | | | | | | |
| | | 6.2 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 8.6 mineral mix | | | | | | | | | | | | |
| | | 19 olive oil | 20 | 40 | | | | | 0 v. other DIO diets | nr | – | – | nr | |
| | | 31.2 maize starch | | | | | | | | | | | | |
| | | 11.2 sucrose | | | | | | | | | | | | |
| | | 22.4 casein | | | | | | | | | | | | |
| | | 6.2 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 8.6 mineral mix | | | | | | | | | | | | |
| | | 19 safflower-seed oil | 20 | 40 | | | | | 0 v. other DIO diets | nr | – | – | nr | |
| | | 31.2 maize starch | | | | | | | | | | | | |
| | | 11.2 sucrose | | | | | | | | | | | | |
| | | 22.4 casein | | | | | | | | | | | | |
| | | 6.2 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 8.6 mineral mix | | | | | | | | | | | | |
| | | 20 lard | 20 | 39.4 | nr | nr | nr | 12 | i v. high-oleic safflower-seed oil and linseed oil | nr | | | 0 v. other DIO diets | 18 |
| | | 39.8 maize starch | | | | | | | | | | | | |
| | | 24 casein | | | | | | | | | | | | |
| | | 5 sucrose | | | | | | | | | | | | |
| | | 5 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 4.2 mineral mix | | | | | | | | | | | | |
| | | 0.4 DL-methionine | | | | | | | | | | | | |
| | | 0.3 choline | | | | | | | | | | | | |
| | | 0.002 α-tocopherol | | | | | | | | | | | | |
| | | 20 high-oleic safflower-seed oil | 20 | 39.4 | | | | | d v. lard | nr | d v. lard | nr | 0 v. other DIO diets | |
| | | 39.8 maize starch | | | | | | | | | | | | |
| | | 24 casein | | | | | | | | | | | | |
| | | 5 sucrose | | | | | | | | | | | | |
| | | 5 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 4.2 mineral mix | | | | | | | | | | | | |
| | | 0.4 DL-methionine | | | | | | | | | | | | |
| | | 0.3 choline | | | | | | | | | | | | |
| | | 0.002 α-tocopherol | | | | | | | | | | | | |
| | | 20 safflower-seed oil | 20 | 39.4 | | | | | 0 v. other DIO diets | nr | d v. lard | nr | 0 v. other DIO diets | |
| | | 39.8 maize starch | | | | | | | | | | | | |
| | | 24 casein | | | | | | | | | | | | |
| | | 5 sucrose | | | | | | | | | | | | |
| | | 5 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 4.2 mineral mix | | | | | | | | | | | | |
| | | 0.4 DL-methionine | | | | | | | | | | | | |
| | | 0.3 choline | | | | | | | | | | | | |
| | | 0.002 α-tocopherol | | | | | | | | | | | | |
| | | 20 linseed oil | 20 | 39.4 | | | | | d v. lard | nr | d v. lard | nr | 0 v. other DIO diets | |
| | | 39.8 maize starch | | | | | | | | | | | | |
| | | 24 casein | | | | | | | | | | | | |
| | | 5 sucrose | | | | | | | | | | | | |
| | | 5 cellulose | | | | | | | | | | | | |
| | | 1.2 vitamin mix | | | | | | | | | | | | |
| | | 4.2 mineral mix | | | | | | | | | | | | |
| | | 0.4 DL-methionine | | | | | | | | | | | | |
| | | 0.3 choline | | | | | | | | | | | | |
| | | 0.002 α-tocopherol | | | | | | | | | | | | |
| Yaqoob <i>et al.</i> (1995) ⁽⁴³⁾ | Rats, Lewis, male, 65–85 g, 3 weeks | g/100 g | | | g/100 g | | | | | | Epididymal | | kcal | |

Table 1. Continued

| Diet composition | | | | | | | | | | | | | | Changes in body weight and dietary intake | | | | |
|--|-------------------------------------|---|---------------|-------------------|---|---------------|-------------------|------------------|--|--|--|---------------------------|---|---|--|--|--|--|
| Reference | Species, strain, sex, weight, age | DIO diet | Amount of fat | | Control diet | Amount of fat | | Duration (weeks) | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | Line no. | | | | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | | | | | | | | | | |
| Ikemoto <i>et al.</i> (1996) ⁽⁵²⁾ | Mice, C57BL/6J, female, nr, 7 weeks | 20 coconut oil 1 maize oil 0-0004 cholesterol 20 protein 49-5 carbohydrate 5 non-nutritive bulk 0-12 vitamin E | 21 | 40-5 | 14-6 protein 48-4 carbohydrate 18-6 non-nutritive bulk 0-01vitamin E 2-4 unspecified oil 0-0001 cholesterol | 2-4 | 6 | 10 | i | i | i i v. other DIO diets | i 0 v. other DIO diets | d v. olive oil, evening primrose oil, fish oil, control | 19 | | | | |
| | | 20 olive oil 1 maize oil 0-0004 cholesterol 20 protein 49-5 carbohydrate 5 non-nutritive bulk 0-12 vitamin E | 21 | 40-5 | | | | | i d v. fish oil | i d v. fish oil | i d v. coconut oil | i 0 v. other DIO diets | i v. coconut oil | | | | | |
| | | 20 safflower-seed oil 1 maize oil 0-0004 cholesterol 20 protein 49-5 carbohydrate 5 non-nutritive bulk 0-12 vitamin E | 21 | 40-5 | | | | | i | i | i d v. coconut oil i v. evening primrose oil, fish oil | i 0 v. other DIO diets | 0 v. other DIO diets | | | | | |
| | | 20 evening primrose oil 1 maize oil 0-0004 cholesterol 20 protein 49-5 carbohydrate 5 non-nutritive bulk 0-12 vitamin E | 21 | 40-5 | | | | | i d v. fish oil | i d v. fish oil | i d v. coconut oil, safflower-seed oil | i 0 v. other DIO diets | i v. coconut oil | | | | | |
| | | 20 fish oil 1 maize oil 0-0004 cholesterol 20 protein 49-5 carbohydrate 5 non-nutritive bulk 0-12 vitamin E | 21 | 40-5 | | | | | i i v. olive oil and evening primrose oil | i i v. olive oil and evening primrose oil | i d v. coconut oil, safflower-seed oil | i 0 v. other DIO diets | i v. coconut oil | | | | | |
| | | g/100 g | | | g/100 g | | | | | | Parametrial | | kcal | | | | | |
| | | 32 palm oil 33-1 casein 17-6 sucrose 1-4 vitamin mix 9-8 mineral mix 5-6 cellulose powder 0-5 DL-methionine | 32 | 60 | 4 safflower-seed oil 23-7 casein 10 sucrose 50 starch 1 vitamin mix 7 mineral 4 cellulose powder 0-4 DL-methionine | 4 | 11 | 19 | i | i | i | nr | 0 d v. fish oil | 20 | | | | |
| | | 32 lard 33-1 casein 17-6 sucrose 1-4 vitamin mix 9-8 mineral mix 5-6 cellulose powder 0-5 DL-methionine | 32 | 60 | | | | | i | i | i | nr | 0 i v. perilla oil | | | | | |
| | | 32 fish oil 33-1 casein 17-6 sucrose 1-4 vitamin mix 9-8 mineral mix 5-6 cellulose powder 0-5 DL-methionine | 32 | 60 | | | | | 0 | 0 | 0 | nr | i i v. palm oil, rapeseed oil, perilla oil | | | | | |
| | | 32 perilla oil 33-1 casein 17-6 sucrose 1-4 vitamin mix 9-8 mineral mix 5-6 cellulose powder 0-5 DL-methionine | 32 | 60 | | | | | i | i | i | nr | 0 d v. lard, safflower-seed oil, fish oil | | | | | |

[illegible]

Table 1. Continued

| Reference | Species, strain, sex, weight, age | DIO diet | Diet composition | | | | Duration (weeks) | Changes in body weight and dietary intake | | | | | | Line no. |
|--|--|--------------------------------------|------------------|-------------------|---|---------------|------------------|---|-------------------------|-----------------------------------|--------------------------------------|----------------------|-------------------|----------|
| | | | Amount of fat | | Control diet | Amount of fat | | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | | | | | | | % of total energy | |
| Cha & Jones (1998) ⁽⁶²⁾ | Rats, Sprague–Dawley, male, 209 ± 6.5 g, nr | g/100 g | | | | | | | | | | | | |
| | | 20 fish oil | 20 | 36 | nr | nr | nr | 10 | 0 v. other DIO diets | nr | d v. safflower-seed oil, beef tallow | 0 v. other DIO diets | nr | 23 |
| | | 15 casein | | | | | | | | | | | | |
| | | 45 maize starch | | | | | | | | | | | | |
| | | 10 sucrose | | | | | | | | | | | | |
| | | 5 cellulose | | | | | | | | | | | | |
| | | 3.5 mineral mix | | | | | | | | | | | | |
| | | 1 vitamin mix | | | | | | | | | | | | |
| | | 0.18 L-cystine | | | | | | | | | | | | |
| | | 0.25 choline bitartrate | | | | | | | | | | | | |
| | | 0.004 <i>tert</i> -butylhydroquinone | | | | | | | | | | | | |
| | | 20 safflower-seed oil | 20 | 36 | | | | | 0 v. other DIO diets | nr | i v. beef tallow, fish oil | 0 v. other DIO diets | nr | |
| 15 casein | | | | | | | | | | | | | | |
| 45 maize starch | | | | | | | | | | | | | | |
| 10 sucrose | | | | | | | | | | | | | | |
| 5 cellulose | | | | | | | | | | | | | | |
| 3.5 mineral mix | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | |
| 0.18 L-cystine | | | | | | | | | | | | | | |
| 0.25 choline bitartrate | | | | | | | | | | | | | | |
| 0.004 <i>tert</i> -butylhydroquinone | | | | | | | | | | | | | | |
| 20 beef tallow | 20 | 36 | | | | | | 0 v. other DIO diets | nr | i v. fish oil | 0 v. other DIO diets | nr | | |
| 15 casein | | | | | | | | | | d v. safflower-seed oil | | | | |
| 45 maize starch | | | | | | | | | | | | | | |
| 10 sucrose | | | | | | | | | | | | | | |
| 5 cellulose | | | | | | | | | | | | | | |
| 3.5 mineral mix | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | |
| 0.18 L-cystine | | | | | | | | | | | | | | |
| 0.25 choline bitartrate | | | | | | | | | | | | | | |
| 0.004 <i>tert</i> -butylhydroquinone | | | | | | | | | | | | | | |
| Loh <i>et al.</i> (1998) ⁽¹⁰⁴⁾ | Rats, Zucker, genetically obese and lean, male, lean: 112–113 g, obese: 132–136 g, 5 weeks | g/100 g | | | g/100 g | | | | | | | Total | kcal | |
| | | 35.8 soyabean oil | 35.8 | 65 | 6.85 soyabean | 6.8 | 15 | 8 | 0 | 0 | 0 | nr | i (only in obese) | 24 |
| | | 23.5 casein | | | 19.5 casein | | | | | d v. palm olein (only in obese) | d v. palm olein (only in obese) | | | |
| | | 2.7 sucrose | | | 53.6 sucrose | | | | | | | | | |
| | | 15 maize starch | | | 10 maize starch | | | | | | | | | |
| | | 17.9 fibre | | | 5 fibre | | | | | | | | | |
| | | 1 vitamin mix | | | 1 vitamin mix | | | | | | | | | |
| | | 3.5 mineral mix | | | 3.5 mineral mix | | | | | | | | | |
| | | 0.3 L-cysteine | | | 0.3 L-cysteine | | | | | | | | | |
| | | 0.25 choline chloride | | | 0.25 choline chloride | | | | | | | | | |
| | | 30 palm olein | 35.8 | 65 | | | | | i (only in obese) | i (only in obese) | i (only in obese) | nr | i (only in obese) | |
| | | 5.8 soyabean oil | | | | | | | | i v. soyabean oil (only in obese) | i v. soyabean oil (only in obese) | | | |
| 23.5 casein | | | | | | | | | | | | | | |
| 2.7 sucrose | | | | | | | | | | | | | | |
| 15 maize starch | | | | | | | | | | | | | | |
| 17.9 fibre | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | |
| 3.5 mineral mix | | | | | | | | | | | | | | |
| 0.3 L-cysteine | | | | | | | | | | | | | | |
| 0.25 choline chloride | | | | | | | | | | | | | | |
| George <i>et al.</i> (2000) ⁽¹²⁸⁾ | Mice, C57B/6J, female, nr, 9–10 weeks | g/100 g | | | | | | | | | | | | |
| | | Cocoa butter | 17.5 | nr | Purina chow (Purina Rodent Laboratory Chow, no. 5001) | 8.25 | nr | 15 | 0 | nr | – | nr | nr | 25 |
| | | | | | | | | | 0 v. safflower-seed oil | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|------|----|---|-----|-----|----|---|---|--|----|---------------------------------|----|
| | | Safflower-seed oil | 17.5 | nr | | | | | 0 | nr | — | nr | nr | |
| Harrold <i>et al.</i> (2000) ⁽⁴¹⁾ | Rats, Wistar, male, 150 g, 6 weeks | g/100 g | | | | | | | 0 v. cocoa butter | | | | kJ | |
| | | 33 Nestlé condensed milk 7 sucrose 33 ground pellet | 6.3 | 13 | Standard pellet (CRM Bio-sure, Cambridge, UK) 9 fat 65 carbohydrate 24 protein | 4.3 | 9.2 | 8 | i (high weight-gainers only) 0 (low weight-gainers only) i (high v. low weight-gainers) | i (high weight-gainers only) 0 (low weight-gainers only) i (high v. low weight-gainers) | Epididymal and perirenal i (high v. low weight-gainers) | nr | i (high v. low weight-gainers) | 26 |
| Ainslie <i>et al.</i> (2000) ⁽³⁹⁾ | Rats, Wistar, female, 223–233 g, 20–22 weeks | | | | | | | | | | | | kJ | |
| | | 10 ml fat emulsion (Intralipid; Kabi Pharmacia, AB, Stockholm) + non-purified laboratory diet (not specified) | 20 | 36 | Non-purified diet (not specified) | 3 | 6.5 | 14 | i | nr | Abdominal, infrarenal and subcutaneous i | nr | i | 27 |
| Ghibaudi <i>et al.</i> (2002) ⁽²⁴⁾ | Rats, Sprague–Dawley, male, 50–60 g, weaning | % of total energy | | | % of total energy | | | | | | Total | | kcal | |
| | | 45 fat 35 carbohydrate 20 protein (D12451; Research Diets, New Brunswick, NJ, USA) | 26 | 45 | 10 fat 70 carbohydrate 20 protein (D12450B; Research Diets) | 4.6 | 10 | 26 | i | i | i | nr | i | 28 |
| | | 32 fat 51 carbohydrate 17 protein (D12266; Research Diets) | 17 | 32 | | | | | 0 | 0 | 0 | nr | 0 | |
| Levin & Dunn-Meynell (2002) ⁽⁸²⁾ | Rats, Sprague–Dawley (DIO and DR), male, DR: 282–327 g, DIO: 368–402 g, 10–12 weeks | g/100 g | | | | | | | | | Epididymal, retroperitoneal, perirenal and mesenteric | | kcal | |
| | | 8 maize oil 44 sweetened condensed milk 48 Purina chow (Purina Rat Chow, no. 5008) % of total energy 31 fat 48 carbohydrate 21 protein DIO diet + chocolate-flavoured liquid diet (Ensure®; Ross Products Division, Medical Supplies Depot, AL, USA) % of total energy 22 fat 64 carbohydrate 14 protein | 16.6 | 31 | Purina chow (Purina Rat Chow, no. 5008) | 4.5 | 9.6 | 10 | i (Only in DIO) d v. Ensure® i v. DIO diet | i (Only in DIO) d v. Ensure® i v. DIO diet | i (Only in DIO) d v. Ensure® i v. DIO diet | nr | 0 d v. Ensure® i v. DIO diet | 29 |
| Levin & Dunn-Meynell (2002) ⁽⁴⁶⁾ | Rats, Sprague–Dawley (DIO and DR), male, 300–425 g, nr | g/100 g | | | | | | | | | Total | | | |
| | | 8 maize oil 44 sweetened condensed milk 48 Purina chow (Purina Rat Chow, no. 5001) % of total energy 31 fat 48 carbohydrate 21 protein | 16.6 | 31 | nr | nr | nr | 4 | i v. DR | nr | i v. DR | nr | nr | 30 |
| Ellis <i>et al.</i> (2002) ⁽⁵³⁾ | Rats, Sprague–Dawley, female, 61 g, 3 weeks | g/100 g | | | g/100 g | | | | | | Total, % change | | kcal | |

Table 1. Continued

| Reference | Species, strain, sex, weight, age | DIO diet | Diet composition | | Control diet | Amount of fat | | Duration (weeks) | Changes in body weight and dietary intake | | | | | | Line no. |
|---|---|-------------------------|------------------|-------------------|------------------------|---------------|-------------------|-----------------------------|---|--|--|---|----------------------|----|----------|
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | | |
| | | | | | | | | | | | | | | | |
| Rolland <i>et al.</i> (2002) ⁽¹⁰⁵⁾ | Rats, Zucker (lean and obese), male, obese: 227 ± 12 g; lean: 196 ± 12 g, 6 weeks | 20 maize oil | 20 | 40 | 2-4 maize oil | 2-4 | 6 | 8 | i | i | i | nr | 0 | 31 | |
| | | 22-6 casein | | | 18-2 casein | | | | i v. coconut oil (only in low-fat diet) | i v. coconut oil (only in low-fat diet) | i v. coconut oil (only in low-fat diet) | | | | |
| | | 45-4 dextrin | | | 70-5 dextrose | | | | | | | | | | |
| | | 0-5 DL-methionine | | | 0-4 DL-methionine | | | | | | | | | | |
| | | 1-5 vitamin mix | | | 1-5 vitamin mix | | | | | | | | | | |
| | | 3 mineral mix | | | 3 mineral mix | | | | | | | | | | |
| | | 4 cellulose | | | 4 cellulose | | | | | | | | | | |
| | | 20 rapeseed oil | 20 | 40 | 2-4 rapeseed oil | 2-4 | 6 | | i | i | i | nr | 0 | | |
| | | 22-6 casein | | | 18-2 casein | | | | | i v. coconut oil (only in low-fat diet) | i v. coconut oil (only in low-fat diet) | | | | |
| | | 45-4 dextrin | | | 70-5 dextrose | | | | | | | | | | |
| Wang <i>et al.</i> (2002) ⁽⁶⁰⁾ | Mice, C57BL/6J, male, nr, 3 weeks | 20 coconut oil | 20 | 40 | 2-4 coconut oil | 2-4 | 6 | | i | i | i | nr | 0 | | |
| | | 22-6 casein | | | 18-2 casein | | | | d v. maize oil (only in low-fat diets) | d v. rapeseed oil, maize oil (only in low-fat diets) | d v. rapeseed oil, maize oil (only in low-fat diets) | | | | |
| | | 45-4 dextrin | | | 70-5 dextrose | | | | | | | | | | |
| | | 0-5 DL-methionine | | | 0-4 DL-methionine | | | | | | | | | | |
| | | 1-5 vitamin mix | | | 1-5 vitamin mix | | | | | | | | | | |
| | | 3 mineral mix | | | 3 mineral mix | | | | | | | | | | |
| | | 4 cellulose | | | 4 cellulose | | | | | | | | | | |
| | | g/100 g | | | g/100 g | | | | | | | Total | | | |
| | | 17-1 butter | 17-1 | 30 | nr | nr | nr | 11 | i v. soyabean oil (only in obese) | nr | i v. soyabean oil (only in obese) | i v. soyabean oil | nr | 32 | |
| | | 54-4 starch | | | | | | | d v. soyabean oil (only in lean) | | | | | | |
| 20-4 casein | | | | | | | | | | | | | | | |
| 2 cellulose | | | | | | | | | | | | | | | |
| 5 mineral mix | | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | | |
| 0-15 methionine | | | | | | | | | | | | | | | |
| 14-1 soyabean oil | 14-7 | 27 | | | | | | d v. butter (only in obese) | nr | d v. butter (only in obese) | | nr | | | |
| 56-5 starch | | | | | | | | i v. butter (only in lean) | | | | | | | |
| 21-2 casein | | | | | | | | | | | | | | | |
| 2 cellulose | | | | | | | | | | | | | | | |
| 5 mineral mix | | | | | | | | | | | | | | | |
| 1 vitamin mix | | | | | | | | | | | | | | | |
| 0-15 methionine | | | | | | | | | | | | | | | |
| | | g/100 g | | | g/100 g | | | | | | | | | | |
| | | 16-9 beef tallow | 16-9 | 58 | 4-1 safflower-seed oil | 4-1 | 10 | 7 | nr | nr | i | d v. high-fat safflower-seed oil (week 5–7) | i | 33 | |
| | | 16-9 maize starch | | | 43-8 maize starch | | | | | | i v. fish oil | | 0 v. other DIO diets | | |
| | | 8-5 sucrose | | | 23-9 sucrose | | | | | | | | | | |
| | | 25-4 casein | | | 18-8 casein | | | | | | | | | | |
| | | 1-9 gelatin | | | 1-4 gelatin | | | | | | | | | | |
| | | 5-1 bran | | | 3-8 bran | | | | | | | | | | |
| | | 6-7 mineral mix | | | 5 mineral mix | | | | | | | | | | |
| | | 1-3 vitamin mix | | | 0-97 vitamin mix | | | | | | | | | | |
| | | 0-3 methionine | | | 0-23 methionine | | | | | | | | | | |
| | | 16-9 safflower-seed oil | 16-9 | 58 | 4-1 safflower-seed oil | 4-1 | 10 | 7 | nr | nr | 0 | i v. high-fat beef tallow (week 5–7) | i | | |
| | | 16-9 maize starch | | | 43-8 maize starch | | | | | | | | 0 v. other DIO diets | | |
| | | 8-5 sucrose | | | 23-9 sucrose | | | | | | | | | | |
| | | 25-4 casein | | | 18-8 casein | | | | | | | | | | |
| | | 1-9 gelatin | | | 1-4 gelatin | | | | | | | | | | |
| | | 5-1 bran | | | 3-8 bran | | | | | | | | | | |
| | | 6-7 mineral mix | | | 5 mineral mix | | | | | | | | | | |
| | | 1-3 vitamin mix | | | 0-97 vitamin mix | | | | | | | | | | |
| | | 0-3 methionine | | | 0-23 methionine | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|--|---|------|------|---|-----|------|----|--------------------|---------------------------|-----------------------|----|---------------------------|----|
| Jen <i>et al.</i> (2003) ⁽¹⁰²⁾ | Rats, Wistar, female, nr, 3 weeks | 16.9 fish oil 16.9 maize starch 8.5 sucrose 25.4 casein 1.9 gelatin 5.1 bran 6.7 mineral mix 1.3 vitamin mix 0.3 methionine | 16.9 | 58 | | | | | nr | nr | d d v. beef tallow | nr | i 0 v. other DIO diets | |
| | | g/100 g | | | g/100 g | | | | | | Abdominal fat | | kcal | |
| | | 40 soyabean oil 26 casein 0.65 maize starch 0.217 maltodextrin 20 maltose dextrin 6.5 cellulose 0.008 butylhydroquinone 4.5 salt mix 1.3 vitamin mix 0.039 vitamin E 0.39 L-cystine 0.325 choline bitartrate 33 palm oil 7 soyabean oil 26 casein 0.65 maize starch 0.217 maltodextrin 20 maltose dextrin 6.5 cellulose 0.008 butylhydroquinone 4.5 salt mix 1.3 vitamin mix 0.039 vitamin E 0.39 L-cystine 0.325 choline bitartrate 33 fish oil 7 soyabean oil 26 casein 0.65 maize starch 0.217 maltodextrin 20 maltose dextrin 6.5 cellulose 0.008 butylhydroquinone 4.5 salt mix 1.3 vitamin mix 0.039 vitamin E 0.39 L-cystine 0.325 choline bitartrate | 40 | 65.4 | 7 soyabean oil 20 casein 32.1 maize starch 10.72 maltodextrin 20 maltose dextrin 5 cellulose 0.008 butylhydroquinone 3.5 salt mix 1 vitamin mix 0.03 vitamin E 0.3 L-cystine 0.25 choline bitartrate | 7 | 15.9 | 6 | i i v. fish oil | nr | i i v. fish oil | nr | 0 d v. palm oil | 34 |
| | | | | | | | | | | | | | | |
| Woods <i>et al.</i> (2003) ⁽⁴²⁾ | Rats, Long-Evans, male and female, 250–350 g, 9–10 weeks | 19 butter oil 1 soyabean oil 16.4 casein 30.3 maize starch 11.5 dextrose 8.9 sucrose 5.8 cellulose 5.2 mineral mix 1.17 vitamin mix 0.21 L-cystine 0.29 choline bitartrate % of total energy | 20 | 40 | 3 butter oil 1 soyabean oil 14 casein 45.5 maize starch 15.5 dextrose 10 sucrose 5 cellulose 4.5 mineral mix 1 vitamin mix 0.18 L-cystine 0.25 choline bitartrate % of total energy | 4 | 8 | 10 | i | nr | i | nr | i | 35 |
| | | g/100 g | | | g/100 g | | | | | | Total | | kJ | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Huang <i>et al.</i> (2004) ⁽⁵¹⁾ | Mice, C57BL/6J, male, nr, 3 weeks | 59 fat 14 carbohydrate 27 protein (not specified) | 38.9 | 59 | 10 fat 63 carbohydrate 27 protein (company not specified) | 4.6 | 10 | 13 | nr | i (only in obesity prone) | – | nr | i | 36 |
| | | g/100 g | | | | | | | | | | | | |
| Silva <i>et al.</i> (2006) ⁽¹²¹⁾ | Rats, Wistar, male, nr, 3 weeks | | | | | | | | | | Epididymal | | | |

Table 1. Continued

| Reference | Species, strain, sex, weight, age | DIO diet | Diet composition | | | | Changes in body weight and dietary intake | | | | | | | Line no. |
|--|--|--|------------------|-------------------|----------------------|---------------|---|------------------|--|---|---|--|--------------------------|----------|
| | | | Amount of fat | | Control diet | Amount of fat | | Duration (weeks) | Final/daily body weight (g) | Body-weight gain (g) | Body fat (g) | Food intake (g) | Energy intake | |
| | | | g/100 g diet | % of total energy | | g/100 g diet | % of total energy | | | | | | | |
| Okere <i>et al.</i> (2006) ⁽⁶¹⁾ | Rats, Wistar, male, 329 ± 9.7 g, 8–9 weeks | 7 soyabean oil 15 casein 67.9 maize starch 5 cellulose 3.5 mineral mix 1 vitamin mix 1.8 L-cystine 0.25 choline | 7 | 16 | nr | | | 3–4 | d v. palm oil and hydrogenated vegetable oil | nr | d v. palm oil and hydrogenated vegetable oil | 0 v. other DIO diets (starting week 3) | – | 37 |
| | | 5 palm oil 2 soyabean oil 15 casein 67.9 maize starch 5 cellulose 3.5 mineral mix 1 vitamin mix 1.8 L-cystine 0.25 choline | 7 | 16 | nr | | | 3–4 | i v. soya oil and rapeseed oil | nr | i v. soya oil, rapeseed oil and hydrogenated vegetable oil | 0 v. other DIO diets (starting week 3) | – | |
| | | 6 rapeseed oil 1 soyabean oil 15 casein 67.9 maize starch 5 cellulose 3.5 mineral mix 1 vitamin mix 1.8 L-cystine 0.25 choline | 7 | 16 | | | | | d v. palm oil and hydrogenated vegetable oil | nr | d v. palm oil and hydrogenated vegetable oil | 0 v. other DIO diets (starting week 3) | – | |
| | | 6 hydrogenated vegetable oil 1 soyabean oil 15 casein 67.9 maize starch 5 cellulose 3.5 mineral mix 1 vitamin mix 1.8 L-cystine 0.25 choline | 7 | 16 | | | | | i v. soya oil and rapeseed oil | nr | i v. soya oil and rapeseed oil d v. palm oil | 0 v. other DIO diets (starting week 3) | – | |
| | | | | | | | | | | | Abdominal, epididymal and intra-thoracic | | kcal | |
| | | Cocoa butter (Research Diets, New Brunswick, NJ, USA) | nr | 60 | Purina chow (Teklad) | 4.7 | 10 | 8 | 0 0 v. other DIO diet | 0 0 v. other DIO diet | i i v. safflower-seed oil (intra-thoracic) | nr | 0 0 v. other DIO diet | 38 |
| | | | | | | | | | | d d v. safflower-seed oil (epididymal and abdominal) | | | | |
| | | Safflower-seed oil (Research Diets, New Brunswick, NJ, USA) | nr | 60 | | | | | 0 0 v. other DIO diet | 0 0 v. other DIO diet | 0 i v. cocoa butter (epididymal and abdominal) d v. cocoa butter (intra-thoracic fat) | nr | 0 0 v. other DIO diet | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |

nr, Not reported; i, increase v. control diet or as specified; 0, no change or difference v. control diet or as specified; –, not measured; d, decrease v. control diet or as specified; DR, dietary obesity resistant.

overweight adult female Wistar rats led to a lower final weight and fat mass in medium-chain fatty acid-fed animals⁽¹³¹⁾. Similarly, lower body weight and fat gain were found in adult male Sprague–Dawley rats fed medium-chain TAG-rich high-fat diets (at 50 % of energy) for 8 weeks than in rats fed high-fat diets based on long-chain fatty acids⁽¹³²⁾. Other studies in animals^(133–135) and in human subjects^(136,137) reported similar findings.

The location of the terminal double bond of PUFA may affect their action. Diets rich in *n*-3 fatty acids have been shown to prevent obesity better than other subclasses of PUFA^(56,116). This effect has been reported in studies in human subjects^(57,138,139), mice^(48,60) and rats^(62,63,65,66,102). In most of the animal studies lower fat deposition in subjects fed *n*-3 fatty acids was shown despite comparable food and energy intake among the groups^(48,60,62,65,66) (Table 1; lines 12, 33, 23, 22 and 14, respectively); therefore this effect can be related to the metabolic effects of *n*-3 fats. Suggested mechanisms involved in this effect of *n*-3 PUFA are: (1) low expression of lipogenic transcription genes with diets high in *n*-3 PUFA^(59,60,116,118); (2) increased concentrations of thromboxane A₂, leukotriene B₄ and some cytokines that are elevated by an increase in *n*-6 PUFA intake and decrease in *n*-3 PUFA, and a low dietary *n*-6:*n*-3 ratio is beneficial for preventing them⁽¹⁴⁰⁾; (3) inhibition of PG synthesis by *n*-3 PUFA leading to suppression of terminal differentiation of adipocytes⁽⁶⁵⁾.

The configuration of the double bonds of PUFA may also affect the development of obesity. Conjugated fatty acids are PUFA that have at least one double bond separated by one single bond. Conjugated linoleic acid was shown to prevent obesity, and this effect has been attributed to: lower energy intake by decreasing the expression of neuropeptide Y and agouti-related protein, increased diet-induced thermogenesis, decreased pre-adipocyte differentiation via decreasing the expression of PPAR γ which is a key factor for adipogenesis, and decreased lipogenesis through decreasing lipoprotein lipase activity and fatty acid synthase expression^(141,142). The antiobesity effect of conjugated linoleic acid was reported in studies conducted in rodents^(143,144) and human subjects^(145,146). However, animal⁽¹⁴⁷⁾ and human⁽¹⁴⁸⁾ studies have found that feeding conjugated linoleic acid-rich diets might also lead to insulin resistance.

The studies mentioned varied in species, strain, age and/or sex of the animals used, which may explain some divergences among the results. Using different fats or fatty acids at various percentages of animal or plant origin and in a wide range of durations might have affected the results as well. For example, in a diet containing 40 %⁽⁴⁷⁾ or 58 %⁽⁶⁰⁾ energy as beef tallow (48 % SFA and 52 % PUFA), the percentages of SFA and PUFA would be 19 and 21 % (in the 40 % diet) and 28 and 30 % (in the 58 % diet), respectively. These percentages might have been high enough to reveal the obesogenic effect of SFA when used for a 7–8-week period. The source of fat (plant origin *v.* animal origin) also might have affected the results, for example, because SFA of plant origin might not be as effective as SFA of animal origin in developing obesity. Indeed, SFA of plant origin mainly contain medium-chain fatty acids (lauric acid in coconut oil and palm kernel oil)

rather than long-chain fatty acids which are abundant in fats of animal origin⁽¹⁴⁹⁾.

Taken together, the findings indicate that rats and mice are appropriate models for studying the effects of various fatty acids in developing obesity.

Physiological mechanisms of high-fat diet-induced obesity

Food efficiency and diet-induced thermogenesis

Some reports have attributed obesity induced by high-fat diets to their high food efficiency (g body-weight gain per kJ food consumed). Energy from fat has a larger effect on body-weight gain than has energy from non-fat sources^(12,14,22,49,106,150,151). Diet-induced thermogenesis is the energy for digesting, absorbing and storing nutrients and produces a loss of energy for the body which is 2–3 % for fats, 25–30 % for proteins and 6–8 % for carbohydrates. Therefore, the efficiency of nutrient utilisation differs among macronutrients and fats have an efficiency of 97–98 %, whereas efficiency is 70–75 % for proteins and 92–94 % for carbohydrates^(10,12,22,112). In addition, it costs energy to build long-chain fatty acids from glucose or amino acids, whereas dietary fat contains long-chain fatty acid pre-formed.

Energy density

Some studies have shown that a fat-rich diet induces obesity by increasing energy intake^(24,38,39,41,42). If weight of intake is not increased at least in proportion, this implicates the high energy density of high-fat diets.

Individuals with *ad libitum* access to diets with different energy densities ate the same amount of food by weight (in a meal or over a few days)^(72,152–155). On the other hand, after 2 weeks of exposure, subjects learned to compensate for the higher energy density of the diet, and ate less weight of food⁽¹⁵⁶⁾. Rats and mice have been labelled as hyperphagic when fed a fat-rich diet, which was based on animals ingesting more energy and not necessarily weight of food^(24,39,42,51). Although in the mentioned studies, the weight of food ingested was not always reported, rats might have attempted to adjust their intake according to the energy density of the fat-rich diet. While some of the high-fat diets were less dense in other macronutrients and micronutrients, rats could not fully adjust for the extra dietary energy while ingesting a minimal amount of the high-fat diet to meet their requirements (for example, 5 % protein for maintenance and 15 % for growth)⁽¹⁵⁷⁾ with carrying extra energy. Therefore, high-fat diets used to induce obesity in animal models should meet macronutrient and micronutrient requirements of the animals, so that hyperphagia can be better interpreted.

Satiating effects of fat

Weaker satiety signals from fat than from carbohydrates and proteins have been suggested to play a role in over-consumption of energy from fat-rich diets^(69,70,158,159). To clarify if the hyperphagia from fat-rich diets is due to their post-ingestive effect, rats were administered by gastric self-infusion for 16 d isoenergetic high-fat (59.9 % of

energy) and high-carbohydrate (fat: 16.7 % of energy) liquid diets⁽¹⁶⁰⁾. Rats self-infused more energy per d of the high-fat diet than of the high-carbohydrate diet; thus, when orosensory effects are minimised, hyperphagia on high-fat diets remains. Poorly satiating post-ingestive effects of fat produced more frequent meals and resulted in large meals⁽¹⁶⁰⁾.

Post-ingestive effect of nutrients also may increase food intake by conditioning sensory preference⁽¹⁵⁹⁾. In a 9 d study, adult female Sprague–Dawley rats were infused intragastrically with isoenergetic high-fat (59.6 % of energy) and high-carbohydrate (14.6 % of energy) diets paired with different flavours (cherry, grape or strawberry). The rats drank substantially more (38 %) of the solution paired with the infusion of the high-fat diet than the solution paired with the infusion of the high-carbohydrate diet, hence the post-ingestive effect of the diets high in fat enhances preference for the sensory features of high-fat diets⁽¹⁵⁹⁾.

Various mechanisms have been suggested for a reduction in satiety signals with high-fat feeding and attenuation of suppression of energy intake by high-fat diets. These include: (1) attenuated enterogastric inhibition of gastric emptying and secretion of satiety hormones (cholecystokinin, peptide YY (PYY) and glucagon-like peptide-1) which are normally stimulated by the presence of fat in the small intestine, and thus decrease late satiety^(161,162); (2) inhibition of fatty acid oxidation^(163,164), so that high-fat diets lower the rate of oxidation of fatty acids, hence they may increase intake; (3) insensitivity to the food intake reducing the effect of apoA-IV, which is a peptide that decreases meal size^(165,166). Low-energy-dense diets have greater volume and so induce more stomach distension than diets with higher energy density⁽¹³⁾.

Hormones

Signals from adipose tissue (leptin, adiponectin and resistin), stomach (ghrelin and obestatin), pancreas (insulin) and intestine (cholecystokinin, PYY and incretins including glucagon-like peptide-1 and gastric-inhibitory peptide) are sent to the brain to regulate energy balance^(167–169). The present review reports the most extensively studied hormonal effects on energy balance (by reducing energy expenditure or increasing energy intake) associated with high-fat feeding.

Leptin. Leptin, first identified in 1994 by Rockefeller University scientists, is an important hormone in the control of food intake and body weight⁽¹⁷⁰⁾. It is as an obese gene product produced by adipose tissue, generally in proportion to fat mass, with rises in plasma levels resulting in a decrease in food intake and increase in energy expenditure^(170–174). Plasma leptin levels display a circadian rhythm. In humans, leptin is increased during the night and peak values are reached at about 24.00 hours, while minimum values are found at midday^(175,176). Studies in human subjects have shown that obesity is associated with higher concentrations of plasma leptin⁽¹⁷⁶⁾. Moreover, in healthy men, leptin levels increased in response to a high-fat meal; however, no differential effects among fatty acid chain length or saturation were reported⁽¹⁷⁷⁾.

Laboratory rats have similar circadian variations of plasma leptin, although maximum levels are reached in the middle of their active phase (at night) and minimum levels in the middle of their resting phase (daytime)^(178,179). In a study in weanling male and female normal FVB mice, 12 weeks of feeding a high-fat diet (Western diet, Teklad Adjusted Calories Western-Type Diet, no. 88187, fat at 40 % of total energy; Harlan-Teklad, Madison, WI, USA) produced 2.6- to 4.6-fold elevation in plasma leptin levels (measured between 09.00 and 11.00 hours) relative to control mice fed chow, but intake of energy was not less than that of the chow-fed controls⁽¹⁸⁰⁾. Higher leptin levels were also found after a 2 h high-fat meal at dark onset compared with pre-meal levels in adult male obesity-prone Sprague–Dawley rats⁽¹⁸¹⁾.

In adult male Osborne–Mendel rats, adapted to a high-fat diet (56 % of energy) for 2 weeks, no reduction in food intake at 2, 4, 6 and 24 h following intraperitoneal injection of leptin (0.5 mg/kg body weight) after an overnight fast was found⁽¹⁸²⁾. In contrast, when the rats had been adapted to a low-fat diet, the injection suppressed the food intake at all time points. Thus, the intake response to peripheral leptin was impaired by chronically high levels of fat intake⁽¹⁸²⁾. Harrold *et al.*⁽⁴¹⁾ found hyperleptinaemia after 1 week of feeding adult male Wistar rats a raised level of energy as fat (13 % of energy). Levin & Dunn-Meynell⁽⁴⁶⁾ showed that when adult male Sprague–Dawley rats were fed a high-fat diet (31 % of energy) for 1 week and were then switched to 3 weeks of chow feeding, leptin levels (time of sampling not mentioned) were higher in rats that were prone to developing obesity on the high-fat diet than in rats that were resistant to dietary obesity despite having comparable body weights. Both obesity-prone and -resistant Sprague–Dawley rats fed high-fat diets (at 20 % of total energy) showed resistance to the anorectic effect of centrally administered leptin (10 µg; intracerebroventricular; ICV), while control animals fed a low-fat diet (3 % of total energy) decreased their energy intake following leptin administration⁽⁹⁵⁾. However, in another study resistant animals did not show compromised responsiveness to the food-lowering effect of leptin when fed high-fat diets⁽¹⁸³⁾. Overall, these results indicate that high-fat feeding induces hyperleptinaemia and leptin resistance and that this effect is independent of obesity-induced leptin resistance.

The mechanism thought to be involved in hyperleptinaemia and leptin resistance on the high-fat diet involves hypothalamic leptin receptors and their signalling pathways⁽¹⁸⁰⁾. Animals susceptible to dietary obesity have reduced hypothalamic leptin receptor gene expression and show an early leptin response to an increase in dietary fat⁽¹⁸⁴⁾.

In contrast to this, Ainslie *et al.*⁽³⁹⁾ showed that female hooded Wistar rats aged between 20 and 22 weeks fed a high-fat diet (36 % of energy) for 4 weeks had significantly lower plasma leptin levels (measured after an overnight fast) than control rats fed low-fat diets (6.5 % of energy)⁽³⁹⁾. A more recent study showed that adult male Sprague–Dawley rats fed a high-fat diet (60 % of energy) for 2 weeks were hypersensitive to the food intake-lowering effect of ICV administration of leptin (3 µg); however, after 5 weeks on the high-fat diet, rats became insensitive to this effect of injected leptin⁽¹⁸⁵⁾. Another study in weanling C57BL/6J

mice led to similar conclusions⁽¹⁸⁶⁾. The researchers suggested that early in high-fat feeding, animals are sensitive to the food-lowering effect of leptin but despite the reduction in food intake animals become fat as a result of the increase in food efficiency, leading to an increase in plasma leptin levels that is followed by insensitivity to its action⁽¹⁸⁶⁾. This implies that leptin resistance after long-term feeding on a high-fat diet is an effect of the obese state rather than the cause of obesity development.

Animal studies found that the fatty acid composition of a high-fat diet may influence leptin levels in the circulation. Lower serum leptin levels (measured 3–6 h after initiation of the dark phase) were found in 8-week-old lean male Wistar rats fed a diet rich in long-chain SFA (cocoa butter at 60 % of energy) than in animals fed a diet rich in long-chain PUFA (safflower-seed oil at the same percentage) or chow for 8 weeks⁽⁶¹⁾. Although total body fat was similar across dietary groups, SFA-fed rats had less abdominal and epididymal fat, and more intrathoracic fat compared with the other groups. Another study found that adult male Sprague–Dawley rats fed a beef tallow-based diet for 10 weeks had lower leptin levels than animals fed safflower-seed or fish oil, while fish oil-fed animals had the lowest amount of perirenal fat⁽⁶²⁾. These studies suggest that the site of fat accumulation depends on the fatty acid profile of the diet, and various adipose tissue depots can differently contribute to circulating leptin. However, no differences were found between moderate-SFA and -MUFA beef tallow, high-PUFA safflower-seed oil and high-*n*-3 PUFA fish oil in the increased fasting leptin levels in adult male Sprague–Dawley rats fed these diets for 10 weeks⁽¹⁸⁷⁾. Greater leptin levels were found in weanling C57BL/6 male mice fed high-fat diets (at 58 % of energy) based on beef tallow for 7 weeks than mice fed high-fat diets based on fish oil, safflower-seed oil or animals fed low-fat diets (at 10 % of energy); leptin levels were correlated with body fat as well⁽⁶⁰⁾. Similar results were found in other studies^(102,188).

Ghrelin. Ghrelin is a peptide released by cells in the fundus of the stomach that stimulates the release of growth hormone from the pituitary and was identified by Kojima *et al.* in 1999⁽¹⁸⁹⁾. Ghrelin rises before and falls after each *ad libitum* meal and increases food intake^(190,191). In humans ghrelin levels peak in the morning (08.00 hours), at noon (12.00 to 13.00 hours) and in the evening (17.00 to 19.00 hours) and fall after each peak⁽¹⁹²⁾. Obese individuals have lower fasting ghrelin levels than lean individuals and reduced suppression of ghrelin secretion after a meal^(193–196). A fat-rich meal has a smaller suppressive effect on plasma ghrelin concentration than a carbohydrate-rich meal regardless of obesity status⁽¹⁹⁷⁾. So far, no effect of dietary fatty acid profile on total ghrelin levels has been reported^(177,198).

In rats there is a peak of plasma levels of ghrelin 5 h after light onset (resting phase) which remains relatively high for 9 h⁽¹⁷⁸⁾. There is also a second rise just before the beginning of the dark phase, followed by a sharp drop and then a gradual rise during the remainder of the dark phase⁽¹⁹⁹⁾. Ghrelin gene expression and plasma ghrelin concentrations have been found to be lower in mice with dietary obesity than in their lean counterparts, coupled with a decrease in sensitivity to the orexigenic effects of ghrelin as well as

impairment in suppression of ghrelin in response to a meal^(200,201). A study was conducted by Liu *et al.*⁽²⁰²⁾ in two strains of rats with different susceptibilities to develop obesity (Osborne–Mendel prone and S5B/P1 resistant) fed a diet high in fat (56 % of energy) for 2 weeks. Ghrelin gene expression was increased in the stomach of fasted susceptible rats but plasma ghrelin concentrations remained unchanged, while in resistant rats both expression and plasma levels of ghrelin remained unchanged. This indicated that ghrelin may play a role in susceptibility to dietary obesity. In adult Long–Evans rats, 2 weeks of high-fat feeding (70 % of energy) was associated with lower levels of ghrelin than was feeding on a high-carbohydrate diet⁽²⁰³⁾. In an attempt to distinguish between the effects of a high-fat diet and of dietary obesity on ghrelin concentrations, Greeley *et al.*⁽²⁰⁴⁾ fed adult male Sprague–Dawley rats high- (45 % of energy) or low (12 % of energy)-fat diets for 3 weeks. Both groups were tested with triiodothyronine (T₃) to prevent accumulation of fat. Decreased ghrelin levels in high-fat-fed animals were not restored by T₃ treatment, despite the fact that the groups had comparable weights. Moreover, duodenal and jejunal infusion of fat suppressed plasma ghrelin less than glucose and amino acids in adult male Sprague–Dawley rats⁽²⁰⁵⁾.

The mechanisms suggested for ghrelin's actions are twofold. It stimulates hypothalamic secretion of neuropeptide Y that increases food intake, decreases fat oxidation and utilisation of fat and plays a role in meal initiation^(190,203). Ghrelin also decreases the utilisation of fat⁽¹⁹¹⁾. High-fat diets are known to down-regulate ghrelin secretion^(200,203) and an inverse relationship between leptin and ghrelin has been reported⁽²⁰³⁾. On the other hand, hypothalamic expression of ghrelin receptors was enhanced and ghrelin levels were greater in adult male Wistar rats fed a fat-rich meal⁽²⁰⁶⁾. Thus, regulation of ghrelin concentration through fat intake remains inconclusive.

Since suppression of ghrelin levels after a meal is associated with postprandial satiety, the lower suppression of ghrelin secretion following high-fat diets might be an explanation for hyperphagia on high-fat diets. Thus, in an environment with abundant high-fat foods, impairment of ghrelin suppression after a meal leads to overconsumption of energy and induces obesity. Furthermore, the obesity itself impairs the suppression of ghrelin secretion after a meal which further exacerbates the development of obesity.

Insulin. Obesity is associated with elevated basal plasma insulin levels and resistance to the metabolic effects of insulin^(77,207). Independent of obesity, high-fat feeding itself contributes to impaired glucose tolerance and insensitivity to the blood glucose-lowering effect of insulin^(207,208). The fatty acid profile of the diet plays a crucial role in insulin resistance dependent on a high-fat diet^(207–209). In a human study, intake of SFA and MUFA was positively correlated with plasma levels of glucose and insulin⁽²¹⁰⁾. Replacing SFA with MUFA had no beneficial effect on blood glucose and insulin levels during 4 weeks of high-fat feeding in adult overweight and obese men⁽¹¹⁹⁾. On the other hand, some studies have shown beneficial effects of MUFA intake on glucose homeostasis and insulin sensitivity⁽²¹¹⁾.

Animal studies have also shown that hyperinsulinaemia and insulin resistance are induced by high-fat feeding^(42,166,212). In female C57BL/6J mice fed high-fat diets (at 10, 20, 30, 40, 50 and 60 % of total energy) for 15 weeks, a linear relationship between the percentage of dietary fat and glucose intolerance was found⁽²⁶⁾. This dose-dependent effect was also seen in weanling male Sprague–Dawley rats fed diets with different percentages of energy as fat (10, 32, 45 %)⁽²⁴⁾.

Mechanisms of the hyperinsulinaemia and insulin resistance with high-fat diets and obesity are discussed in reviews by Lichtenstein & Schwab⁽²⁰⁷⁾, and Riccardi *et al.*⁽²⁰⁸⁾. These authors suggest that decreases in insulin receptors, glucose transport and metabolism are involved, plus reduction in liver and muscle glycogen synthase activity and storage of glucose as glycogen^(207,208). These abnormalities thus develop when the intake of fat is more than 40 % of total energy. Excessive amounts of adipose tissue (hypertrophy and hyperplasia) stress the endoplasmic reticulum, resulting in secretion of cytokines and decrease in the responsiveness of the cells to insulin⁽⁷⁷⁾.

Differences among dietary fatty acids affect the composition of the cell membranes and this in turn influences the affinity of receptors for insulin and so its action on the cell^(207,208,213). Some studies have found that insulin secretion and sensitivity are enhanced as the degree of unsaturation of fatty acids increases, especially with *n*-3 feeding, and thus feeding diets rich in SFA results in more insulin resistance than MUFA and PUFA^(116,207,208,213). In a study in 7-week-old female C57BL/6J mice fed high-fat diets (60 % of energy) composed of palm oil, lard, fish oil, perilla oil or rapeseed oil for 18 weeks, blood glucose levels were higher in all the high-fat-fed animals 30, 60 and 120 min after an oral glucose challenge than in the group fed a high-carbohydrate–low-fat diet (fat: 11 % of energy), but the increase in fasting blood insulin levels was only reliable in the group fed palm oil⁽⁵²⁾. In weanling female Wistar rats, no difference in insulin levels was found between soyabean oil and palm oil groups⁽¹⁰²⁾, whereas lower plasma insulin levels were found in adult male Wistar rats fed a high-fat diet (60 % of energy) rich in SFA (cocoa butter) than in the control animals (10 % of energy)⁽⁶¹⁾. These disparities might be related to different fats used in these studies: palm oil and cocoa butter differ in SFA content and so diets will vary in SFA at the different percentages of total energy used in the studies. The same can be said for lard, soyabean oil and safflower-seed oil. Beneficial effects of *n*-3 PUFA on action of insulin are reported in many studies^(52,62,214,215).

Since human and animal studies have shown comparable relationships of hormones to obesity, these models can be used to clarify the uncertain areas such as effects of fatty acid profile of the diet on these hormones. However, relating hormone action to obesity itself requires demonstration of its effect on energy intake and/or expenditure.

Behavioural mechanisms of high-fat diet-induced obesity

As discussed in the previous sections, one explanation why high-fat diets induce obesity is hyperphagia^(24,38,39,41,42), i.e. increased weight or volume of daily dietary intake.

Effects of energy density were reviewed earlier. A possible lack of inhibitory effects of fats on intake ('satiety') was discussed above. Here the intake-facilitatory effects of sensory characteristics (or palatability) of high-fat diets will be considered^(13,22,69,70). Feeding rhythmicity^(216,217), social environment^(5,218–228) and stress^(229–231) may also promote obesity. Each of these will be reviewed below. Because social environment is not documented in relation to high fat intake, only feeding rhythmicity and stress will be reviewed below.

Sensory facilitation of intake

Facilitation of intake by the sensory characteristics of high-fat foods is an important influence on ingestion. Sensory stimulation from food consumption can influence energy intake directly⁽²³²⁾, by promoting selection, consumption, digestion and absorption of a food⁽²³³⁾. It also increases diet-induced thermogenesis^(234,235). Foods high in fat are usually preferred by rats to those that are low in fat and are consumed in greater amounts as a result^(13,70,156,236). A variety of sensory properties contribute to this high palatability of fat-rich diets, mainly texture and odour^(69,160,237,238).

In a study on adult male Long–Evans rats, Warwick & Weingarten⁽¹⁶⁰⁾ compared the sensory effects of a high-fat (59.9 % of energy) and a high-carbohydrate diet (fat at 16.7 % of energy). In order to minimise the post-ingestive effect of diets on intake, they used a preparation in which most of the ingested liquid food drained out of the stomach via a fistula. When both diets were offered simultaneously, rats consumed more of the high-fat diet than the high-carbohydrate diet, demonstrating a sensory preference. Warwick *et al.*⁽²³⁸⁾ concluded from a study in weanling female Sprague–Dawley rats that consuming high-fat diets early in life can lead to a sensory preference for this fat product which is relatively stable.

Evidence for sensory preferences for fats in rat and mouse animal models is likely to be based on NEFA released from the TAG in food^(239,240). Lingual lipase has such activity in rodents; taste receptor cells in the oral cavity of rats can easily detect these NEFA; these gustatory signals are transmitted to the brain where they cause release of neurotransmitters such as dopamine and endorphin^(239–241). Long-chain PUFA stimulate T-cell receptors more efficiently and thus are more strongly preferred than other types of fatty acid⁽²⁴¹⁾. Preference for fat is also found in humans, with textural, olfactory and gustatory cues being involved⁽²⁴²⁾.

Rhythmicity of feeding

Rhythmicity in feeding (variation over time in total amount ingested, size and frequency of meals) may play a role in the development of obesity. In human subjects, a lower risk of obesity was reported in both adults and children with a high frequency of eating episodes^(216,217,243). A greater number of meals each day was consumed by obese women than healthy-weight women in Sweden in a cross-sectional survey⁽²⁴⁴⁾. However, similar meal patterns were found in

obese and healthy-weight Swedish men in a dietary survey⁽²⁴⁵⁾.

Time of eating also may play a role in the development of obesity. In humans, meals eaten late in the evening have been suggested to be one of the risk factors of obesity^(217,246). In free-living individuals food intake in the morning was more satiating and associated with less overall intake throughout the day than evening food⁽⁵⁾. However, in another study, percentage energy from evening food intake and weight changes were unrelated⁽²⁴⁷⁾. Taylor *et al.*⁽²⁴⁸⁾ and Bellisle⁽²⁴⁹⁾ suggested that the effects of meal patterns on human obesity have yet to be clarified.

Unlike humans, rats are nocturnal animals that ingest 70–80 % of their food during the dark phase⁽²⁵⁰⁾. There are two peaks in meal frequency and rate of intakes: at the beginning of the night and towards the end, i.e. dusk and dawn feeding^(251,252). In adult male Wistar rats fed a stock diet containing 10 % energy as fat, the greater intake during the dark phase resulted in positive energy balance and fat deposition, with negative energy balance along with the oxidation of fat in the light phase over fourteen 24 h cycles^(250,253). Altered circadian rhythmicity of intake characterised by larger meal size and decreased meal frequency has been found in genetically obese animals fed non-purified diets^(252,254–257).

Some animal studies have found a relationship between sizes of meals and susceptibility to obesity. Adult male Sprague–Dawley rats that ingested chow in larger meals had a higher rate of weight gain when fed high-fat diets than rats that were fed on chow in smaller meals⁽²⁵⁸⁾. When weanling male obesity-prone Sprague–Dawley rats were fed high-fat diets (45 % of energy) for 19 weeks, they ate larger meals than resistant animals⁽²⁵⁹⁾. In adult inbred obesity-prone and -resistant rats fed chow, on the other hand, the obesity-prone rats ingested smaller meals more frequently⁽²⁶⁰⁾. These results suggest that an irregular meal pattern is not a cause of developing obesity in obesity-prone animals. A 6 h meal pattern analysis during the dark phase in adult male Sprague–Dawley rats exposed to isoenergetic high- and low-fat diets (soya oil at 38 and 10 % of total energy) for 2 weeks revealed comparable amounts of food ingested in the first meal, but less food ingested in the second and third meal of high-fat-fed rats, as well as greater meal frequency, shorter inter-meal interval (IMI) and lower rate of weight gain than animals fed the low-fat diet⁽²⁶¹⁾. However, when feeding period was prolonged to 8 weeks, the size of the second meal and IMI increased. Increased meal size and decreased meal frequency have also been found in rats acclimatised to a mixture of high-fat and high-carbohydrate diets (providing 38.5 % energy as fat) for 14 d and then fed a fat-rich diets (at 60 % of total energy) for an additional 8 d⁽²⁶²⁾.

There is a shift of food intake from the dark phase to the light phase in genetically obese rats and mice^(254–256). Mistlberger *et al.*⁽²⁶³⁾ reported higher weight gain in genetically obese Zucker rats when fed *ad libitum* than in those fed only during the 14 h dark phase, while both groups had similar food intakes. In addition, rats differ in their macronutrient selection during the light–dark cycle. It has been reported that when rats are offered a two- or three-way selection between macronutrients, they eat more

carbohydrate at the beginning of the dark phase, and more protein and fat at the end of the dark phase and during the light period⁽²⁶⁴⁾. Thus it is probable that, with high-fat feeding, more food will be ingested in the light period that may further facilitate the development of obesity.

Obesity-prone rats respond more than resistant animals with an increase in meal size. This might account for the hyperphagia with high-fat feeding in dietary obesity. Further research is needed to find out the cause–effect relationship between eating patterns and obesity.

Stress

Many studies have shown that long-term stress increases food intake and promotes weight and fat gain in human subjects^(265,266). In addition, obesity was found to be associated with depression⁽²⁶⁷⁾. Higher levels of obesity in depressed individuals as well as higher prevalence of depression in overweight and obese women and extremely obese men (BMI ≥ 40 kg/m²) were found^(268,269). Depressed individuals with eating disorders often describe themselves as chronically stressed and usually are obese, suggesting that they eat more when stressed in an attempt to cope with the situation and feel better⁽²³⁰⁾. Energy-dense foods with high fat and sugar are known as ‘comfort food’ and are more often eaten during stress^(229,266,270). On the other hand, some individuals show loss of appetite during stress⁽²⁷¹⁾. It has been suggested that this difference is based on the dieting history of the individual: usually dieters increase and non-dieters decrease their intake while in a stressful situation⁽²⁷¹⁾.

A different pattern of responsiveness to stress has been shown in a variety of rodent models^(99,272–274). Rowland & Antelman⁽²⁷⁴⁾ discovered that in adult female Sprague–Dawley rats mild stress induced by six daily sessions (10–15 min) of pinching of the tail for 5 d at equal intervals while they had free access to sweetened milk and tap water resulted in greater food intake and body-weight gain than in the control animals. However, chronic exposure of adult male Sprague–Dawley rats to an immobilisation stressor led to a decrease in food intake, independent of the duration of the stress, while handling stress did not result in change in food intake⁽²⁷³⁾.

Obesity-prone and -resistant animals are also different in their responsiveness to stress. A study was conducted by Levin *et al.*⁽²⁷²⁾ in 2.5-month-old selectively bred male obesity-prone and -resistant Sprague–Dawley rats fed a high-fat diet (31 % of energy) for 1 week. They were then randomly assigned to a stress group or control group while fed the high-fat diet for 3 weeks and then the high-fat diet plus Ensure® (Ross Products Division, Medical Supplies Depot, AL, USA) for another 2 weeks. Rats in the stress group had daily exposure to different stressors for 5 weeks, which were restraint for 15 min, moving the animal to the cage of another, exposure to another male rat for 10 min, 2 min swimming or saline injection. Results showed that stressed obesity-resistant rats gained less weight without any decrease in energy intake with little effect of the stressors on body-weight gain and energy intake of obesity-prone animals. Adding Ensure® to the high-fat diet increased energy intake and rate of weight gain in resistant

animals, but cumulative weight gain over 5 weeks was still lower in stressed rats than in control animals. Weight gain and intake of the obesity-prone rats were unaffected by the addition of Ensure®. It was suggested that resistant rats had a lowered sympathetic activity compared with their unstressed controls, which was shown by lower noradrenaline levels in their urine.

The effect of a high-fat diet on weight gain after stress was investigated in a study in 3- to 4-month-old male obesity-prone and -resistant Sprague–Dawley rats that were restrained once for 20 min, and after release were presented either a high-fat diet (at 31 % of energy) or chow for 9 d⁽⁹⁹⁾. Stressed prone rats fed the high-fat diet gained more weight than unstressed prone rats fed the same diet while having similar food intakes. However, when stressed prone rats were fed chow, they gained less weight than unstressed prone rats fed the same diet. These results showed that prone rats were less responsive to the weight-reducing effect of immobilisation stress when fed a high-fat diet; at the same time they were more responsive to this effect when fed chow. Immobilisation stress had no effect on body-weight gain in resistant rats fed either diet⁽⁹⁹⁾. In another study, adult male Sprague–Dawley rats fed high-fat (at 40 % of total energy) or low-fat diets (at 12 % of total energy) for 4 d were divided into two groups of stressed (restraint tubes with no food and water access followed by tail blood sampling, 3 h daily for three consecutive days) and mildly stressed rats (moved to new cages, food and water deprived for the same period and blood sampled)⁽²⁷⁵⁾. On the days of restraint, stressed rats lost weight regardless of the diet. High-fat-fed mildly stressed animals stopped gaining weight; however, low-fat-fed mildly stressed rats gained weight throughout the experiment⁽²⁷⁵⁾. Results showed that low- and high-fat diets resulted in similar body-weight changes under a severe stress, whereas with a mild stress high-fat-fed animals were more responsive to the weight-lowering effect of stress. In adult male Long–Evans rats, the weight loss resulting from chronic stress was regained after recovery from stress and body-weight and fat gain were greater in high-fat-fed rats than in chow-fed control animals⁽²⁷⁶⁾. Higher preference for high-fat feeding during chronic stress was reported in mice⁽²⁷⁷⁾.

Mechanisms that influence food intake during acute and chronic stress are different. Physiologically, the initial response of the body to an acute stress is secretion of corticotrophin-releasing factor from the paraventricular nucleus of the hypothalamus that stimulates the secretion of adrenocorticotropin hormone from the anterior pituitary which in turn leads to the release of cortisol from the adrenal cortex to provide energy for the brain and/or muscles. Then cortisol itself makes a negative feedback for its further secretion. However, with a chronic exposure to stressor, the negative feedback does not work efficiently and thus induces an increase in food intake and body-weight gain through increased secretion of glucocorticoids which elevate appetite, food intake and fat storage especially in the abdomen^(230,231,278). In adult male Wistar rats, a chronic stress of keeping rats in cages filled with water to a height of 2 cm for 5 d led to delayed gastric emptying during the first 24 h of exposure, but after that it was accelerated and exceeded that of the control group by day 5. In addition,

catecholamines were increased during the first 24 h and then decreased while active ghrelin levels were high on day 3 and remained elevated until day 5⁽²⁷⁹⁾. It was suggested that the increased sympathetic activity after 24 h stimulated ghrelin secretion, and therefore the increased food intake found during chronic stress might be a result of enhanced plasma ghrelin. Plasma ghrelin levels were also found to be increased with acute stress⁽²⁸⁰⁾.

Susceptibility to obesity

There is a genetic background for susceptibility to obesity with interacting environmental factors; the environment alone has an impact on the inherent risk of obesity in individuals^(5,6,281–283). This has been shown in many studies in human subjects⁽²⁾.

An underlying genetic predisposition to be obesity prone or resistant is also shown in animal models^(46,184). Rats and mice known as the standard models for studying dietary obesity are different in their susceptibility to obesity: outbred Sprague–Dawley rats, Wistar rats and C57BL/6C mice can be easily categorised to prone and resistant phenotypes with *ad libitum* access to high-fat diets^(7,8,21). There are also strains known as genetically obese, such as Zucker *fafa* rats and *ob/ob* mice^(8,35).

When exposed to high-fat diets, some animals are sensitive to high-fat diet-induced obesity and become obese (obesity-prone animals), while others resist to this obesogenic effect and grow normally (resistant animals)^(82,284). Some researchers have attributed this difference to higher energy intakes in obesity-prone animals^(51,60,97,259,285,286), while others have found similar intakes in prone and resistant animals, and suggested that susceptible animals were capable of storing energy with greater efficiency^(95,287,288).

Suggested mechanisms for the difference between prone and resistant animals in responding to high-fat diets are that prone animals have lower fat oxidation^(40,98,288,289), increased lipoprotein lipase activity in their adipose tissue and no change in lipoprotein lipase activity of their muscles which favours fat storage in these animals^(97,289,290). However, Commerford *et al.*⁽²⁸⁶⁾ fed 7-week-old male Wistar rats high-fat diets (45 % of energy) for 1 or 5 weeks and found comparable fat accumulation and lipogenesis in prone and resistant rats after provided with an isoenergetic ¹⁴C-labelled high-fat meal, suggesting that the increased energy intake is the main reason for accelerated weight gain in prone animals.

Dietary obese-prone animals also had increased arcuate neuropeptide Y mRNA expression (an orexigenic neuropeptide)⁽²⁹¹⁾, decreased noradrenaline turnover and α_2 -adrenoceptor binding in some parts of the hypothalamus (ventromedial, dorsomedial and lateral) compared with resistant animals, as well as in the pancreas and heart, which shows a reduced sympathetic activity in these organs⁽²⁹²⁾. The reduction in noradrenaline turnover in the pancreas leads to an increase in insulin release and development of obesity.

Sex differences

In humans, there are differences between the two sexes in energy expenditure and requirements as well as in fat

metabolism and fat distribution^(293–295). Greater storage of fat in the lower body in females (gynoid) due to lower basal fat oxidation and greater number of α_2 -adrenoceptors, as well as decreased α_2 -adrenergic sensitivity in the abdominal region, all lead to more fat storage in the thigh region and less in the abdomen compared with men who have greater storage of fat in the upper body (android)^(293–295). Moreover women have more subcutaneous fat than men⁽²⁹⁶⁾. Despite all these differences, in a recent review of the genetic studies of obesity in different countries it was shown that overall obesity rates of males and females as determined by BMI were small and inconsistently different, with no indication of obesity in either sex being more prevalent⁽²⁹⁵⁾.

These differences can also be found in animal models of obesity⁽³⁵⁾. In laboratory rats, males gain weight steadily throughout their lives while the body weight of female rats becomes stable in early adulthood⁽²⁹⁷⁾. As a result, female rats are better models for studying obesity during adulthood since they are more like humans in their growth patterns. Besides, more subcutaneous fat is found in females due to higher concentrations of oestrogen and progesterone receptors in these depots while males have more visceral fat related to high concentrations of androgen receptors in this area⁽²⁹⁸⁾.

The sex of the animals may also affect the cellular response of the adipose tissue to high-fat feeding. This was shown in adult rats fed cafeteria diets for 9 weeks which led to a more rapid development of obesity in female rats, and their difference in weight compared with control animals became obvious after 5 d while in males this became significant after 40 d⁽⁴⁴⁾. The same report showed that weight gain of male and female rats fed a supermarket diet is more similar to each other than that of rats fed chow. Therefore, the sex difference in weight gain normally seen in rats is reduced when animals are developing dietary obesity. Female golden hamsters, aged 10 weeks, fed a fat-rich diet (52 % of energy) ate significantly more energy and gained more weight than males⁽¹⁰⁶⁾. Likewise, 10 d old female Wistar rats fed a cafeteria diet for 14 weeks gained more weight than their male counterparts fed the same diet, suggesting less thermogenic capacity in females when fed the cafeteria diet⁽²⁹⁹⁾. A study in 3-month-old Sprague–Dawley rats showed that female rats fed chow had higher food intake and greater increase in ghrelin and decrease in leptin levels than males following a 12 h fast⁽³⁰⁰⁾. Moreover, an interaction between sex and site of fat accumulation was found in 6-week-old NMRI mice given different amounts of fat (17, 27, 43.5, 60 % of energy) for 14 weeks, with more fat accumulation in retroperitoneal and parametrial sites in females, and in subcutaneous depot in males⁽²⁵⁾.

All together, similar to humans, male and female rats have different body fat distribution which makes them appropriate models for studying adipose tissue. Besides, female animal models are better responders to high-fat feeding, mimicking susceptibility to obesity in humans. However, in a recent review, male mice and rats are introduced as 'gold standards' for studying dietary obesity⁽⁷⁾. This might be because of the oestrous cycle of the female animals which is repeated every 4–6 d and can affect the food intake of the animal during this period⁽³⁰¹⁾.

Reversibility

Animal studies have shown that low-fat diets can induce weight loss in dietary obese rats. A reduction in energy intake and obesity reversal was found when adult male Wistar rats fed a high-fat diet at 60 % of total energy for 17 weeks were switched to chow for 13 weeks⁽³⁰²⁾. Decreased energy intake and obesity reversal with significant weight and fat loss were found in weanling male C57BL/6 mice switched from 17 weeks of high-fat feeding (at 58 % of energy) to low-fat feeding (at 11 % of energy) for 17 weeks⁽³⁰³⁾ or after 13 weeks of high-fat feeding (at 59 % of energy) to low-fat feeding (10 % of energy) for 6 weeks⁽⁵¹⁾. Likewise, a reduction in energy intake and a complete reversal of diet-induced obesity were found when 13-week-old female Wistar rats originally fed high-fat diets (at 30 or 60 % of energy provided by Crisco[®]; Proctor & Gamble, Cincinnati, OH, USA) for 8 or 14 weeks were switched to chow⁽¹⁰¹⁾.

In other studies, however, *ad libitum* low-fat feeding was not an efficient method to completely reverse dietary obesity. For example, an initial decline in body weight followed by a plateau have been found in adult male obesity-prone and -resistant Sprague–Dawley rats after switching from 10 weeks of a high-fat diet (at 31 % of energy) to chow feeding for 2 weeks⁽²⁸⁸⁾; however, when animals were restricted on chow to 50 % of their energy intake for 3 weeks, their body weights reached the level of chow-fed control animals. Decline in body weight and a plateau were also found in adult male obesity-prone Sprague–Dawley rats switched from 10 weeks of being fed a high-fat diet (at 31 % of energy) to 7 weeks of chow feeding, although their energy intake was decreased while on chow⁽⁸²⁾. Wade⁽³⁰⁴⁾ reported that young male and female golden hamsters fed a high-fat diet (at 52 % of energy) for 4 weeks and then switched to chow for 4 weeks (fat at 4.5 % energy) decreased their energy intake and lost 80 % of their weight gain from feeding on the fat-rich diet. Adult male obesity-prone Sprague–Dawley rats fed a high-fat diet (at 31 % of energy) for 12 weeks and then switched to chow for 1 week decreased their energy intake (by 10–20 %) but failed to lose weight⁽³⁰⁵⁾.

Both hyperplasia and hypertrophy of fat cells are involved in developing obesity^(77,78,81). A total of 8 weeks of energy restriction in normal-weight adult male Sprague–Dawley rats did not result in hypoplasia despite the significant decrease in body weight and body fat⁽³⁰⁶⁾. When weanling male Sprague–Dawley rats made obese by feeding a diet containing chow, Crisco[®], sweetened condensed milk and sucrose solution for 19 weeks were then food deprived for 8, 15 or 25 d, body weight and fat cell size decreased, but fat cell number was comparable with that of the chow-fed control animals⁽³⁰⁷⁾. Another study in adult male C57BL/6J mice fed a high-fat diet (45 % of energy, Research Diets, New Brunswick, NJ, USA) for 10 weeks and then switched to chow for 2 weeks had similar results⁽³⁰⁸⁾. Centrally administered leptin (10 μ g, ICV) for 4 d in normal-weight adult male Sprague–Dawley rats caused a decrease in the number of inguinal fat cells⁽³⁰⁹⁾. Leptin injections (5 μ g; ICV) over 5 d decreased the number of fat cells in young (aged 3 months) male Sprague–Dawley rats, but not in mature (aged 8 months) animals⁽³¹⁰⁾. This was also found in

a study in mice⁽³⁰⁸⁾. However, a decrease in fat cell number was not found following dietary reversal of obesity in rats and mice^(306–308). These findings contrast with human studies that showed hypoplasia of adipocytes following reversal of obesity^(78,81).

Conclusions

The physiological mechanisms involved in high-fat diet-induced obesity are overconsumption of high-fat diets due to their low satiating effects, the high efficiency of dietary fat in being stored in the body as well as the alterations in the hormones involved in energy balance, such as high-fat diet-induced hyperleptinaemia and hyperinsulinaemia accompanied by leptin and insulin resistance, and lowered suppression of ghrelin secretion following high-fat diets. Among the behavioural mechanisms, the sensory facilitation of intake with high-fat diets is well understood. Meal pattern analysis of high-fat-fed animals in a pre-obese *vs.* obese state could be useful to understand the development of obesity. An area for future research is to investigate whether different patterns of eating in animal models before obesity development can be a predictor of prone and resistant phenotypes, and to assess their feeding circadian rhythms. There has been extensive research on the obesogenic effects of fatty acids with different degrees of saturation but no constant pattern of outcome under different conditions has been found. More work is needed to prove that body weight can be regulated by the fatty acid profile in high-fat diets. An important key point in designing animal studies is that high-fat diets meet animals' minimal nutrient requirements, especially for protein, vitamins and minerals, to eliminate the possibility of overconsumption of the diet to fulfill these nutrient needs. The ineffectiveness of low-fat diets fed *ad libitum* to reverse dietary obesity induced by long-term high-fat feeding stresses the use of restricted regimens. This could help to investigate whether a significant and sustainable weight loss accompanied by decrease in fat cell number can be achieved.

Acknowledgements

The present review was supported by a grant to Professor Louise Thibault by the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN 39636-01). The authors thank Professor David A. Booth for his insightful comments and suggestions.

Both authors contributed equally to the preparation of this paper.

The authors had no conflicts of interest.

References

- World Health Organization (2005) Obesity and overweight. <http://www.who.int/mediacentre/factsheets/fs311/en/index.html>
- Ichihara S & Yamada Y (2008) Genetic factors for human obesity. *Cell Mol Life Sci* **65**, 1086–1098.
- Bouchard C & Tremblay A (1997) Genetic influences on the response of body fat and fat distribution to positive and negative energy balances in human identical twins. *J Nutr* **127**, 943S–947S.
- Farooqi IS & O'Rahilly S (2005) New advances in the genetics of early onset obesity. *Int J Obes* **29**, 1149–1152.
- De Castro JM (2004) Genes, the environment and the control of food intake. *Br J Nutr* **92**, S59–S62.
- Martínez-Hernández A, Enríquez LM, Moreno-Moreno MJ, *et al.* (2007) Genetics of obesity. *Public Health Nutr* **10**, 1138–1144.
- Reuter TY (2007) Diet-induced models for obesity and type 2 diabetes. *Drug Discov Today Dis Models* **4**, 3–8.
- Speakman J, Hambly C, Mitchell S, *et al.* (2007) Animal models of obesity. *Obes Rev* **8**, 55–61.
- James WPT (2008) The epidemiology of obesity: the size of the problem. *J Intern Med* **263**, 336–352.
- Jequier E (2002) Pathways to obesity. *Int J Obes* **26**, S12–S17.
- Rosengren A & Lissner L (2008) The sociology of obesity. In *Obesity and Metabolism*, pp. 260–270 [A Rosengren and L Lissner, editors]. Basel: Karger.
- Hill JO, Melanson EL & Wyatt HT (2000) Dietary fat intake and regulation of energy balance: implications for obesity. *J Nutr* **130**, 284S–288S.
- French S & Robinson T (2003) Fats and food intake. *Curr Opin Clin Nutr Metab Care* **6**, 629–634.
- Bray GA & Popkin BM (1998) Dietary fat intake does affect obesity. *Am J Clin Nutr* **68**, 1157–1173.
- Schrauwen P & Westerterp KR (2000) The role of high-fat diets and physical activity in the regulation of body weight. *Br J Nutr* **84**, 417–427.
- George V, Tremblay A, Despres JP, *et al.* (1990) Effect of dietary fat content on total and regional adiposity in men and women. *Int J Obes* **14**, 1085–1094.
- Popkin BM, Keyou G, Fengying Z, *et al.* (1993) The nutrition transition in China: a cross-sectional analysis. *Eur J Clin Nutr* **47**, 333–346.
- Saris WHM, Astrup A, Prentice AM, *et al.* (2000) Randomized controlled trial of changes in dietary carbohydrate/fat ratio and simple vs complex carbohydrates on body weight and blood lipids: The CARMEN study. The Carbohydrate Ratio Management in European National diets. *Int J Obes* **24**, 1310–1318.
- Tucker LA & Kano MJ (1992) Dietary fat and body fat: a multivariate study of 205 adult females. *Am J Clin Nutr* **56**, 616–622.
- Rothwell NJ & Stock MJ (1984) The development of obesity in animals – the role of dietary factors. *Clin Endocrinol Metab* **13**, 437–449.
- Buettner R, Scholmerich J & Bollheimer LC (2007) High-fat diets: modeling the metabolic disorders of human obesity in rodents. *Obesity* **15**, 798–808.
- Warwick ZS & Schiffman SS (1992) Role of dietary fat in calorie intake and weight gain. *Neurosci Biobehav Rev* **16**, 585–596.
- Boozar CN, Schoenbach G & Atkinson RL (1995) Dietary fat and adiposity – a dose–response relationship in adult male rats fed isocalorically. *Am J Physiol Endocrinol Metab* **268**, E546–E550.
- Ghibaudi L, Cook J, Farley C, *et al.* (2002) Fat intake affects adiposity, comorbidity factors, and energy metabolism of Sprague–Dawley rats. *Obes Res* **10**, 956–963.
- Bourgeois F, Alexiu A & Lemonnier D (1983) Dietary-induced obesity: effect of dietary fats on adipose tissue cellularity in mice. *Br J Nutr* **49**, 17–26.
- Takahashi M, Ikemoto S & Ezaki O (1999) Effect of the fat/carbohydrate ratio in the diet on obesity and oral glucose

- tolerance in C57BL/6J mice. *J Nutr Sci Vitaminol (Tokyo)* **45**, 583–593.
27. Deuel HJ Jr, Movitt E, Hallman LF, *et al.* (1944) Studies of the comparative nutritive value of fats: I. Growth rate and efficiency of conversion of various diets to tissue. *J Nutr* **27**, 107–121.
 28. Deuel HJ Jr, Meserve ER, Straub E, *et al.* (1947) The effect of fat level of the diet on general nutrition: I. Growth, reproduction and physical capacity of rats receiving diets containing various levels of cottonseed oil or margarine fat *ad libitum*. *J Nutr* **33**, 569–582.
 29. Ingle D (1949) A simple means of producing obesity in the rat. *Proc Soc Exp Biol Med* **72**, 604–605.
 30. Fenton PF & Dowling MT (1953) Studies on obesity. 1. Nutritional obesity in mice. *J Nutr* **49**, 319–331.
 31. Sclafani A & Springer D (1976) Dietary obesity in adult rats – similarities to hypothalamic and human obesity syndromes. *Physiol Behav* **17**, 461–471.
 32. Hebert JR, Patterson RE, Gorfine M, *et al.* (2003) Differences between estimated caloric requirements and self-reported caloric intake in the Women's Health Initiative. *Ann Epidemiol* **13**, 629–637.
 33. Poppitt SD, Swann D, Black AE, *et al.* (1998) Assessment of selective under-reporting of food intake by both obese and non-obese women in a metabolic facility. *Int J Obes* **22**, 303–311.
 34. Voss S, Kroke A, Klipstein-Grobusch K, *et al.* (1998) Is macronutrient composition of dietary intake data affected by underreporting? Results from the EPIC-Potsdam Study. *Eur J Clin Nutr* **52**, 119–126.
 35. Thibault L, Woods SC & Westerterp-Plantenga MS (2004) The utility of animal models of human energy homeostasis. *Br J Nutr* **92**, S41–S45.
 36. Young GS & Kirkland JB (2007) Rat models of caloric intake and activity: relationships to animal physiology and human health. *Appl Physiol Nutr Metab* **32**, 161–176.
 37. Mickelsen O, Takahashi S & Craig C (1955) Experimental obesity. 1. Production of obesity in rats by feeding high-fat diets. *J Nutr* **57**, 541–554.
 38. Oscai LB (1982) Dietary-induced severe obesity – a rat model. *Am J Physiol* **242**, R212–R215.
 39. Ainslie DA, Proietto J, Fam BC, *et al.* (2000) Short-term, high-fat diets lower circulating leptin concentrations in rats. *Am J Clin Nutr* **71**, 438–442.
 40. Chang S, Graham B, Yakubu F, *et al.* (1990) Metabolic differences between obesity-prone and obesity-resistant rats. *Am J Physiol* **259**, R1103–R1110.
 41. Harrold JA, Williams G & Widdowson PS (2000) Early leptin response to a palatable diet predicts dietary obesity in rats: key role of melanocortin-4 receptors in the ventromedial hypothalamic nucleus. *J Neurochem* **74**, 1224–1228.
 42. Woods SC, Seeley RJ, Rushing PA, *et al.* (2003) A controlled high-fat diet induces an obese syndrome in rats. *J Nutr* **133**, 1081–1087.
 43. Yaqoob P, Sherrington EJ, Jeffery NM, *et al.* (1995) Comparison of the effects of a range of dietary lipids upon serum and tissue lipid composition in the rat. *Int J Biochem Cell Biol* **27**, 297–310.
 44. Sclafani A & Gorman AN (1977) Effects of age, sex, and prior body weight on the development of dietary obesity in adult rats. *Physiol Behav* **18**, 1021–1026.
 45. Schemmel R, Mickelsen O & Tolgay Z (1969) Dietary obesity in rats: influence of diet, weight, age, and sex on body composition. *Am J Physiol* **216**, 373–379.
 46. Levin BE & Dunn-Meynell AA (2002) Reduced central leptin sensitivity in rats with diet-induced obesity. *Am J Physiol Regul Integr Comp Physiol* **283**, R941–R948.
 47. Bell RR, Spencer MJ & Sherriff JL (1997) Voluntary exercise and monounsaturated canola oil reduce fat gain in mice fed diets high in fat. *J Nutr* **127**, 2006–2010.
 48. Cunnane SC, McAdoo KR & Horrobin DF (1986) *n*-3 Essential fatty acids decrease weight gain in genetically obese mice. *Br J Nutr* **56**, 87–95.
 49. Herberg L, Doppen W, Major E, *et al.* (1974) Dietary-induced hypertrophic–hyperplastic obesity in mice. *J Lipid Res* **15**, 580–585.
 50. Lemonnier D, Suquet JP, Aubert R, *et al.* (1975) Metabolism of mouse made obese by a high-fat diet. *Diabetes Metab* **1**, 77–85.
 51. Huang XF, Xin X, McLennan P, *et al.* (2004) Role of fat amount and type in ameliorating diet-induced obesity: insights at the level of hypothalamic arcuate nucleus leptin receptor, neuropeptide Y and pro-opiomelanocortin mRNA expression. *Diabetes Obes Metab* **6**, 35–44.
 52. Ikemoto S, Takahashi M, Tsunoda N, *et al.* (1996) High-fat diet-induced hyperglycemia and obesity in mice: differential effects of dietary oils. *Metab Clin Exp* **45**, 1539–1546.
 53. Ellis J, Lake A & Hoover-Plow J (2002) Monounsaturated canola oil reduces fat deposition in growing female rats fed a high or low fat diet. *Nutr Res* **22**, 609–621.
 54. Lissner L, Heitmann BL & Bengtsson C (2000) Population studies of diet and obesity. *Br J Nutr* **83**, S21–S24.
 55. Gray-Donald K, Jacobs-Starkey L & Johnson-Down L (2000) Food habits of Canadians: reduction in fat intake over a generation. *Can J Public Health* **91**, 381–385.
 56. Moussavi N, Gavino V & Receveur O (2008) Could the quality of dietary fat, and not just its quantity, be related to risk of obesity? *Obesity* **16**, 7–15.
 57. DeLany JP, Windhauser MM, Champagne CM, *et al.* (2000) Differential oxidation of individual dietary fatty acids in humans. *Am J Clin Nutr* **72**, 905–911.
 58. Kien CL, Bunn JY & Ugrasbul F (2005) Increasing dietary palmitic acid decreases fat oxidation and daily energy expenditure. *Am J Clin Nutr* **82**, 320–326.
 59. Storlien LH, Huang XF, Lin S, *et al.* (2001) Dietary fat subtypes and obesity. *World Rev Nutr Diet* **88**, 148–154.
 60. Wang H, Storlien LH & Huang XF (2002) Effects of dietary fat types on body fatness, leptin, and Arc leptin receptor, NPY, and AgRP mRNA expression. *Am J Physiol Endocrinol Metab* **282**, E1352–E1359.
 61. Okere IC, Chandler MP, McElfresh TA, *et al.* (2006) Differential effects of saturated and unsaturated fatty acid diets on cardiomyocyte apoptosis, adipose distribution, and serum leptin. *Am J Physiol Heart Circ Physiol* **291**, H38–H44.
 62. Cha MC & Jones PJH (1998) Dietary fat type and energy restriction interactively influence plasma leptin concentration in rats. *J Lipid Res* **39**, 1655–1660.
 63. Hill JO, Peters JC, Lin D, *et al.* (1993) Lipid accumulation and body fat distribution is influenced by type of dietary fat fed to rats. *Int J Obes* **17**, 223–236.
 64. Jones PJH, Toy BR & Cha MC (1995) Differential fatty acid accretion in heart, liver and adipose tissues of rats fed beef tallow, fish-oil, olive oil and safflower oils at 3 levels of energy-intake. *J Nutr* **125**, 1175–1182.
 65. Okuno M, Kajiwarra K, Imai S, *et al.* (1997) Perilla oil prevents the excessive growth of visceral adipose tissue in rats by down-regulating adipocyte differentiation. *J Nutr* **127**, 1752–1757.
 66. Su W & Jones PJH (1993) Dietary fatty acid composition influences energy accretion in rats. *J Nutr* **123**, 2109–2114.

67. Preiss-Landl K, Zimmermann R, Hämmerle G, *et al.* (2002) Lipoprotein lipase: the regulation of tissue specific expression and its role in lipid and energy metabolism. *Curr Opin Lipidol* **13**, 471–481.
68. Westerterp-Plantenga MS (2004) Fat intake and energy balance effects. *Physiol Behav* **83**, 579–585.
69. Blundell JE & Macdiarmid JI (1997) Fat as a risk factor for overconsumption: satiation, satiety, and patterns of eating. *J Am Diet Assoc* **97**, S63–S69.
70. Golay A & Bobbioni E (1997) The role of dietary fat in obesity. *Int J Obes* **21**, S2–S11.
71. Rolls BJ (2000) The role of energy density in the overconsumption of fat. *J Nutr* **130**, 268S–271S.
72. Poppitt SD & Prentice AM (1996) Energy density and its role in the control of food intake: evidence from metabolic and community studies. *Appetite* **26**, 153–174.
73. Skelton JA, DeMattia L, Miller L, *et al.* (2006) Obesity and its therapy: from genes to community action. *Pediatr Clin North Am* **53**, 777–794.
74. Kiess W, Petzold S, Topfer M, *et al.* (2008) Adipocytes and adipose tissue. *Best Pract Res Clin Endocrinol Metab* **22**, 135–153.
75. Kershaw EE & Flier JS (2004) Adipose tissue as an endocrine organ. *J Clin Endocrinol Metab* **89**, 2548–2556.
76. Sorisky A (1999) From preadipocyte to adipocyte: differentiation-directed signals of insulin from the cell surface to the nucleus. *Crit Rev Clin Lab Sci* **36**, 1–34.
77. de Ferranti S & Mozaffarian D (2008) The perfect storm: obesity, adipocyte dysfunction, and metabolic consequences. *Clin Chem* **54**, 945–955.
78. Avram MM, Avram AS & James WD (2005) Subcutaneous fat in normal and diseased states – 1. Introduction. *J Am Acad Dermatol* **53**, 663–670.
79. Hirsch J & Han PW (1969) Cellularity of rat adipose tissue – effects of growth starvation and obesity. *J Lipid Res* **10**, 77–82.
80. Greenwood M & Hirsch J (1974) Postnatal development of adipocyte cellularity in normal rat. *J Lipid Res* **15**, 474–483.
81. Prins JB & Orahilly S (1997) Regulation of adipose cell number in man. *Clin Sci* **92**, 3–11.
82. Levin BE & Dunn-Meynell AA (2002) Defense of body weight depends on dietary composition and palatability in rats with diet-induced obesity. *Am J Physiol Regul Integr Comp Physiol* **282**, R46–R54.
83. Lee MO (1929) Determination of the surface area of the white rat with its application to the expression of metabolic results. *Am J Physiol* **89**, 24–33.
84. Li XL, Wu GH, Xie L, *et al.* (2004) Experimental study on the obesity rat model induced by vitamin D. *Chin J Clin Rehab* **8**, 1786–1787.
85. Sun Z, Zhang ZC & Liu ZC (2002) Experimental study of diet-induced obesity animal model. *Chin Pharmacol Bull* **18**, 466–467.
86. Kanarek RB & Markskaufman R (1979) Developmental aspects of sucrose-induced obesity in rats. *Physiol Behav* **23**, 881–885.
87. Li H, Matheny M, Nicolson M, *et al.* (1997) Leptin gene expression increases with age independent of increasing adiposity in rats. *Diabetes* **46**, 2035–2039.
88. Stephens DN (1980) Does the Lee obesity index measure general obesity? *Physiol Behav* **25**, 313–315.
89. Bernardis LL (1970) Sex and age differences in hyperthermia response to ether anesthesia in weanling rats with ventromedial hypothalamic lesions. *Experientia* **26**, 1322–1324.
90. Bernardis LL & Patterson BD (1968) Correlation between ‘Lee index’ and carcass fat content in weanling and adult female rats with hypothalamic lesions. *J Endocrinol* **40**, 527–528.
91. Rogers P & Webb GP (1980) Estimation of body fat in normal and obese mice. *Br J Nutr* **43**, 83–86.
92. Lindsay RS, Hanson RL, Roumain J, *et al.* (2001) Body mass index as a measure of adiposity in children and adolescents: relationship to adiposity by dual energy X-ray absorptiometry and to cardiovascular risk factors. *J Clin Endocrinol Metab* **86**, 4061–4067.
93. Tzotzas T, Krassas GE & Doumas A (2008) Body composition analysis in obesity: radionuclide and non radionuclide methods. *Hell J Nucl Med* **11**, 63–71.
94. Holemans K, Caluwaerts S, Poston L, *et al.* (2004) Diet-induced obesity in the rat: a model for gestational diabetes mellitus. *Am J Obstet Gynecol* **190**, 858–865.
95. Tulipano G, Vergoni AV, Soldi D, *et al.* (2004) Characterization of the resistance to the anorectic and endocrine effects of leptin in obesity-prone and obesity-resistant rats fed a high-fat diet. *J Endocrinol* **183**, 289–298.
96. Dourmashkin JT, Chang GQ, Hill JO, *et al.* (2006) Model for predicting and phenotyping at normal weight the long-term propensity for obesity in Sprague–Dawley rats. *Physiol Behav* **87**, 666–678.
97. Dourmashkin JT, Chang GQ, Gayles EC, *et al.* (2005) Different forms of obesity as a function of diet composition. *Int J Obes* **29**, 1368–1378.
98. Hassanain M & Levin BE (2002) Dysregulation of hypothalamic serotonin turnover in diet-induced obese rats. *Brain Res* **929**, 175–180.
99. Michel C, Levin BE & Dunn-Meynell AA (2003) Stress facilitates body weight gain in genetically predisposed rats on medium-fat diet. *Am J Physiol Regul Integr Comp Physiol* **285**, R791–R799.
100. Lissner L, Levitsky DA, Strupp BJ, *et al.* (1987) Dietary fat and the regulation of energy intake in human subjects. *Am J Clin Nutr* **46**, 886–892.
101. Bartness TJ, Polk DR, McGriff WR, *et al.* (1992) Reversal of high-fat diet-induced obesity in female rats. *Am J Physiol* **263**, R790–R797.
102. Jen KLC, Buisson A, Pellizzon M, *et al.* (2003) Differential effects of fatty acids and exercise on body weight regulation and metabolism in female wistar rats. *Exp Biol Med* **228**, 843–849.
103. Faust IM, Johnson PR, Stern JS, *et al.* (1978) Diet-induced adipocyte number increase in adult rats – new model of obesity. *Am J Physiol* **235**, E279–E286.
104. Loh MY, Flatt WP, Martin RJ, *et al.* (1998) Dietary fat type and level influence adiposity development in obese but not lean Zucker rats. *Proc Soc Exp Biol Med* **218**, 38–44.
105. Rolland V, Roseau S, Fromentin G, *et al.* (2002) Body weight, body composition, and energy metabolism in lean and obese Zucker rats fed soybean oil or butter. *Am J Clin Nutr* **75**, 21–30.
106. Wade GN (1982) Obesity without overeating in golden hamsters. *Physiol Behav* **29**, 701–707.
107. Pichon L, Huneau JF, Fromentin G, *et al.* (2006) A high-protein, high-fat, carbohydrate-free diet reduces energy intake, hepatic lipogenesis, and adiposity in rats. *J Nutr* **136**, 1256–1260.
108. Sinitskaya N, Gourmelen S, Schuster-Klein C, *et al.* (2007) Increasing the fat-to-carbohydrate ratio in a high-fat diet prevents the development of obesity but not a prediabetic state in rats. *Clin Sci* **113**, 417–425.
109. Weigle DS, Breen PA, Matthys CC, *et al.* (2005) A high-protein diet induces sustained reductions in appetite, *ad libitum* caloric intake, and body weight despite

- compensatory changes in diurnal plasma leptin and ghrelin concentrations. *Am J Clin Nutr* **82**, 41–48.
110. Potier M, Darcel N & Tome D (2009) Protein, amino acids and the control of food intake. *Curr Opin Clin Nutr Metab Care* **12**, 54–58.
 111. Blom WAM, Lluch A, Stafleu A, *et al.* (2006) Effect of a high-protein breakfast on the postprandial ghrelin response. *Am J Clin Nutr* **83**, 211–220.
 112. Saris WHM (2006) Macronutrient intake balance and the problem of obesity – old recipes and some new spices. *Aktuel Ernahr Med* **31**, S49–S54.
 113. Morrison CD, Xi X, White CL, *et al.* (2007) Amino acids inhibit AgRP gene expression via an mTOR-dependent mechanism. *Am J Physiol Endocrinol Metab* **293**, E165–E171.
 114. Huang XF, Liu YX, Rahardjo GL, *et al.* (2008) Effects of diets high in whey, soy, red meat and milk protein on body weight maintenance in diet-induced obesity in mice. *Nutr Diet* **65**, S53–S59.
 115. Ailhaud G, Massiera F, Weill P, *et al.* (2006) Temporal changes in dietary fats: role of *n*-6 polyunsaturated fatty acids in excessive adipose tissue development and relationship to obesity. *Prog Lipid Res* **45**, 203–236.
 116. Clarke SD (2000) Polyunsaturated fatty acid regulation of gene transcription: a mechanism to improve energy balance and insulin resistance. *Br J Nutr* **83**, S59–S66.
 117. Lawton GL, Delargy HJ, Brockman J, *et al.* (2000) The degree of saturation of fatty acids influences post-ingestive satiety. *Br J Nutr* **83**, 473–482.
 118. Lichtenbelt WDV, Mensink RP & Westerterp KR (1997) The effect of fat composition of the diet on energy metabolism. *Z Ernahrungswiss* **36**, 303–305.
 119. Piers LS, Walker KZ, Stoney RM, *et al.* (2003) Substitution of saturated with monounsaturated fat in a 4-week diet affects body weight and composition of overweight and obese men. *Br J Nutr* **90**, 717–727.
 120. Shillabeer G & Lau DCW (1994) Regulation of new fat-cell formation in rats – the role of dietary fats. *J Lipid Res* **35**, 592–600.
 121. Silva APS, Guimaraes DED, Mizurini DM, *et al.* (2006) Dietary fatty acids early in life affect lipid metabolism and adiposity in young rats. *Lipids* **41**, 535–541.
 122. Takeuchi H, Matsuo T, Tokuyama K, *et al.* (1995) Diet-induced thermogenesis is lower in rats fed a lard diet than in those fed a high-oleic acid safflower oil diet, a safflower oil diet or a linseed oil diet. *J Nutr* **125**, 920–925.
 123. Casas-Agustench P, Lopez-Uriarte P, Bullo M, *et al.* (2009) Acute effects of three high-fat meals with different fat saturations on energy expenditure, substrate oxidation and satiety. *Clin Nutr* **28**, 39–45.
 124. Piers LS, Walker KZ, Stoney RM, *et al.* (2002) The influence of the type of dietary fat on postprandial fat oxidation rates: monounsaturated (olive oil) vs saturated fat (cream). *Int J Obes* **26**, 814–821.
 125. Soares MJ, Cummings SJ, Mamo JCL, *et al.* (2004) The acute effects of olive oil *v.* cream on postprandial thermogenesis and substrate oxidation in postmenopausal women. *Br J Nutr* **91**, 245–252.
 126. Beardshall K, Morarji Y, Bloom SR, *et al.* (1989) Saturation of fat and cholecystokinin release: implications for pancreatic carcinogenesis. *Lancet* **ii**, 1008–1010.
 127. Alfenas RCG & Mattes RD (2003) Effect of fat sources on satiety. *Obes Res* **11**, 183–187.
 128. George J, Mulkins M, Casey S, *et al.* (2000) The effects of *n*-6 polyunsaturated fatty acid supplementation on the lipid composition and atherogenesis in mouse models of atherosclerosis. *Atherosclerosis* **150**, 285–293.
 129. Nagao K & Yanagita T (2008) Bioactive lipids in metabolic syndrome. *Prog Lipid Res* **47**, 127–146.
 130. Takeuchi H, Sekine S, Kojima K, *et al.* (2008) The application of medium-chain fatty acids: edible oil with a suppressing effect on body fat accumulation. *Asia Pac J Clin Nutr* **17**, 320–323.
 131. Simón E, Fernández-Quintela A, Del Puy Portillo M, *et al.* (2000) Effects of medium-chain fatty acids on body composition and protein metabolism in overweight rats. *J Physiol Biochem* **56**, 337–346.
 132. Takeuchi H, Noguchi O, Sekine S, *et al.* (2006) Lower weight gain and higher expression and blood levels of adiponectin in rats fed medium-chain TAG compared with long-chain TAG. *Lipids* **41**, 207–212.
 133. Bray GA, Lee M & Bray TL (1980) Weight gain of rats fed medium-chain triglycerides is less than rats fed long-chain triglycerides. *Int J Obes* **4**, 27–32.
 134. Hwang SG, Yano H & Kawashima R (1992) The influence of dietary medium and long chain triglycerides on growth performances and fat deposition in growing rats. *J Nutr Sci Vitaminol* **38**, 127–139.
 135. Noguchi O, Takeuchi H, Kubota F, *et al.* (2002) Larger diet-induced thermogenesis and less body fat accumulation in rats fed medium-chain triacylglycerols than in those fed long-chain triacylglycerols. *J Nutr Sci Vitaminol* **48**, 524–529.
 136. Stubbs RJ & Harbron CG (1996) Covert manipulation of the ratio of medium- to long-chain triglycerides in isoenergetically dense diets: effect on food intake in *ad libitum* feeding men. *Int J Obes* **20**, 435–444.
 137. Tsuji H, Kasai M, Takeuchi H, *et al.* (2001) Dietary medium-chain triacylglycerols suppress accumulation of body fat in a double-blind, controlled trial in healthy men and women. *J Nutr* **131**, 2853–2859.
 138. Garaulet M, Perez-Llamas F, Perez-Ayala M, *et al.* (2001) Site-specific differences in the fatty acid composition of abdominal adipose tissue in an obese population from a Mediterranean area: relation with dietary fatty acids, plasma lipid profile, serum insulin, and central obesity. *Am J Clin Nutr* **74**, 585–591.
 139. Nogi A, Yang JJ, Li LM, *et al.* (2007) Plasma *n*-3 polyunsaturated fatty acid and cardiovascular disease risk factors in Japanese, Korean and Mongolian workers. *J Occup Health* **49**, 205–216.
 140. Simopoulos AP (2004) Omega-6/omega-3 essential fatty acid ratio and chronic diseases. *Food Rev Int* **20**, 77–90.
 141. Kennedy A, Martinez K, Schmidt S, *et al.* (2010) Antiobesity mechanisms of action of conjugated linoleic acid. *J Nutr Biochem* **21**, 171–179.
 142. Park Y (2009) Conjugated linoleic acid (CLA): good or bad *trans* fat? *J Food Comp Anal* **22**, Suppl. 1, S4–S12.
 143. Moon HS, Lee HG, Seo JH, *et al.* (2009) Antiobesity effect of ??pegylated conjugated linoleic acid on high-fat diet-induced obese C57BL/6J (*ob/ob*) mice: attenuation of insulin resistance and enhancement of antioxidant defenses. *J Nutr Biochem* **20**, 187–194.
 144. Parra P, Palou A & Serra F (2010) Moderate doses of conjugated linoleic acid reduce fat gain, maintain insulin sensitivity without impairing inflammatory adipose tissue status in mice fed a high fat diet. *Nutr Metab* **7**, 5.
 145. Norris LE, Collene AL, Asp ML, *et al.* (2009) Comparison of dietary conjugated linoleic acid with safflower oil on body composition in obese postmenopausal women with type 2 diabetes mellitus. *Am J Clin Nutr* **90**, 468–476.
 146. Sahin H, Uyanik F & Inanc N (2008) Effects of conjugated linoleic acid on body composition and selected biochemical parameters in obese women. *Pak J Nutr* **7**, 546–549.

147. Halade GV, Rahman MM & Fernandes G (2010) Differential effects of conjugated linoleic acid isomers in insulin-resistant female C57BL/6J mice. *J Nutr Biochem* **21**, 332–337.
148. Ingelsson E & Risérus U (2008) Effects of *trans*10cis 12CLA-induced insulin resistance on retinol-binding protein 4 concentrations in abdominally obese men. *Diabetes Res Clin Pract* **82**, e23–e24.
149. Van Nieuwenhuyzen W & Adelman R (2007) Multipurpose functions of MCT oils – medium chain triglycerides have unique functions. *Agro Food Ind Hi-Tech* **18**, 34–36.
150. Pripic V, Watson PM, Frampton IC, *et al.* (2002) Adaptive changes in adipocyte gene expression differ in AKR/J and SWR/J mice during diet-induced obesity. *J Nutr* **132**, 3325–3332.
151. Roberts CK, Berger JJ & Barnard RJ (2002) Long-term effects of diet on leptin, energy intake, and activity in a model of diet-induced obesity. *J Appl Physiol* **93**, 887–893.
152. Drewnowski A (2003) The role of energy density. *Lipids* **38**, 109–115.
153. Rolls BJ, Bell EA, Castellanos VH, *et al.* (1999) Energy density but not fat content of foods affected energy in lean and obese women. *Am J Clin Nutr* **69**, 863–871.
154. Westerterp-Plantenga MS (2004) Effects of energy density of daily food intake on long-term energy intake. *Physiol Behav* **81**, 765–771.
155. Rolls BJ & Bell EA (1999) Intake of fat and carbohydrate: role of energy density. *Eur J Clin Nutr* **53**, S166–S173.
156. Stubbs RJ & Whybrow S (2004) Energy density, diet composition and palatability: influences on overall food energy intake in humans. *Physiol Behav* **81**, 755–764.
157. Institute for Laboratory Animal Research (1995) *The Nutritional Requirements of Rats*, 4th revised ed. Washington, DC: National Academies Press.
158. Blundell JE, Lawton CL, Cotton JR, *et al.* (1996) Control of human appetite: implications for the intake of dietary fat. *Annu Rev Nutr* **16**, 285–319.
159. Lucas F, Ackroff K & Sclafani A (1998) High-fat diet preference and overeating mediated by postingestive factors in rats. *Am J Physiol Regul Integr Comp Physiol* **275**, R1511–R1522.
160. Warwick ZS & Weingarten HP (1995) Determinants of high-fat diet hyperphagia – experimental dissection of orosensory and postingestive effects. *Am J Physiol Regul Integr Comp Physiol* **269**, R30–R37.
161. Covasa M & Ritter RC (2000) Adaptation to high-fat diet reduces inhibition of gastric emptying by CCK and intestinal oleate. *Am J Physiol Regul Integr Comp Physiol* **278**, R166–R170.
162. Little TJ, Horowitz M & Feinle-Bisset C (2007) Modulation by high-fat diets of gastrointestinal function and hormones associated with the regulation of energy intake: implications for the pathophysiology of obesity. *Am J Clin Nutr* **86**, 531–541.
163. Scharrer E (1999) Control of food intake by fatty acid oxidation and ketogenesis. *Nutrition* **15**, 704–714.
164. Kahler A, Zimmermann M & Langhans W (1999) Suppression of hepatic fatty acid oxidation and food intake in men. *Nutrition* **15**, 819–828.
165. Tso P & Liu M (2004) Apolipoprotein A-IV, food intake, and obesity. *Physiol Behav* **83**, 631–643.
166. Woods SC, D'Alessio DA, Tso P, *et al.* (2004) Consumption of a high-fat diet alters the homeostatic regulation of energy balance. *Physiol Behav* **83**, 573–578.
167. Coll AP, Farooqi IS & O'Rahilly S (2007) The hormonal control of food intake. *Cell* **129**, 251–262.
168. Crowell MD, Decker GA, Levy R, *et al.* (2006) Gut–brain neuropeptides in the regulation of ingestive behaviors and obesity. *Am J Gastroenterol* **101**, 2848–2856.
169. Gale SM, Castracane VD & Mantzoros CS (2004) Energy homeostasis, obesity and eating disorders: recent advances in endocrinology. *J Nutr* **134**, 295–298.
170. Zhang YY, Proenca R, Maffei M, *et al.* (1994) Positional cloning of the mouse obese gene and its human homolog. *Nature* **372**, 425–432.
171. Lin S, Storlien LH & Huang XF (2000) Leptin receptor, NPY, POMC mRNA expression in the diet-induced obese mouse brain. *Brain Res* **875**, 89–95.
172. MacDougald OA, Hwang CS, Fan H, *et al.* (1995) Regulated expression of the obese gene product (leptin) in white adipose tissue and 3T3-L1 adipocytes. *Proc Natl Acad Sci U S A* **92**, 9034–9037.
173. Pelleymounter MA, Cullen MJ, Baker MB, *et al.* (1995) Effects of the obese gene-product on body-weight regulation in *ob/ob* mice. *Science* **269**, 540–543.
174. Halaas JL, Gajiwala KS, Maffei M, *et al.* (1995) Weight-reducing effects of the plasma protein encoded by the obese gene. *Science* **269**, 543–546.
175. Randeve HS, Karteris E, Lewandowski KC, *et al.* (2003) Circadian rhythmicity of salivary leptin in healthy subjects. *Mol Genet Metab* **78**, 229–235.
176. Saad MF, Riad-Gabriel MG, Khan A, *et al.* (1998) Diurnal and ultradian rhythmicity of plasma leptin: effects of gender and adiposity. *J Clin Endocrinol Metab* **83**, 453–459.
177. Poppitt SD, Leahy E, Keogh GF, *et al.* (2006) Effect of high-fat meals and fatty acid saturation on postprandial levels of the hormones ghrelin and leptin in healthy men. *Eur J Clin Nutr* **60**, 77–84.
178. Bodosi B, Gardi J, Hajdu I, *et al.* (2004) Rhythms of ghrelin, leptin, and sleep in rats: effects of the normal diurnal cycle, restricted feeding, and sleep deprivation. *Am J Physiol Regul Integr Comp Physiol* **287**, R1071–R1079.
179. Chacon F, Esquifino AI, Perello M, *et al.* (2005) 24-Hour changes in ACTH, corticosterone, growth hormone, and leptin levels in young male rats subjected to calorie restriction. *Chronobiol Int* **22**, 253–265.
180. Frederich RC, Hamann A, Anderson S, *et al.* (1995) Leptin levels reflect body lipid content in mice: evidence for diet-induced resistance to leptin action. *Nat Med* **1**, 1311–1314.
181. Leibowitz SF, Chang GQ, Dourmashkin JT, *et al.* (2006) Leptin secretion after a high-fat meal in normal-weight rats: strong predictor of long-term body fat accrual on a high-fat diet. *Am J Physiol Endocrinol Metab* **290**, E258–E267.
182. Lin L, Martin R, Schaffhauser AO, *et al.* (2001) Acute changes in the response to peripheral leptin with alteration in the diet composition. *Am J Physiol Regul Integr Comp Physiol* **280**, R504–R509.
183. Surwit RS & Collins S (2001) Revisiting lessons from the C57BL/6J mouse. *Am J Physiol Endocrinol Metab* **280**, E825–E826.
184. Levin BE, Dunn-Meynell AA, Ricci MR, *et al.* (2003) Abnormalities of leptin and ghrelin regulation in obesity-prone juvenile rats. *Am J Physiol Endocrinol Metab* **285**, E949–E957.
185. Fam BC, Morris MJ, Hansen MJ, *et al.* (2007) Modulation of central leptin sensitivity and energy balance in a rat model of diet-induced obesity. *Diabetes Obes Metab* **9**, 840–852.
186. Lin S, Thomas TC, Storlien LH, *et al.* (2000) Development of high fat diet-induced obesity and leptin resistance in C57BL/6J mice. *Int J Obes* **24**, 639–646.
187. Hynes GR, Heshka J, Chadee K, *et al.* (2003) Effects of dietary fat type and energy restriction on adipose tissue fatty

- acid composition and leptin production in rats. *J Lipid Res* **44**, 893–901.
188. Jang IS, Hwang DY, Chae KR, *et al.* (2003) Role of dietary fat type in the development of adiposity from dietary obesity-susceptible Sprague–Dawley rats. *Br J Nutr* **89**, 429–437.
 189. Kojima M, Hosoda H, Date Y, *et al.* (1999) Ghrelin is a growth-hormone-releasing acylated peptide from stomach. *Nature* **402**, 656–660.
 190. Cummings DE, Purnell JQ, Frayo RS, *et al.* (2001) A preprandial rise in plasma ghrelin levels suggests a role in meal initiation in humans. *Diabetes* **50**, 1714–1719.
 191. Tschoep M, Smiley DL & Heiman ML (2000) Ghrelin induces adiposity in rodents. *Nature* **407**, 908–913.
 192. Natalucci G, Riedl S, Gleiss A, *et al.* (2005) Spontaneous 24-h ghrelin secretion pattern in fasting subjects: maintenance of a meal-related pattern. *Eur J Endocrinol* **152**, 845–850.
 193. English PJ, Ghatei MA, Malik IA, *et al.* (2002) Food fails to suppress ghrelin levels in obese humans. *J Clin Endocrinol Metab* **87**, 2984–2987.
 194. Marzullo P, Verti B, Savia G, *et al.* (2004) The relationship between active ghrelin levels and human obesity involves alterations in resting energy expenditure. *J Clin Endocrinol Metab* **89**, 936–939.
 195. Reinehr T, Roth CL, Alexy U, *et al.* (2005) Ghrelin levels before and after reduction of overweight due to a low-fat high-carbohydrate diet in obese children and adolescents. *Int J Obes* **29**, 362–368.
 196. le Roux CW, Patterson M, Vincent RP, *et al.* (2005) Postprandial plasma ghrelin is suppressed proportional to meal calorie content in normal-weight but not obese subjects. *J Clin Endocrinol Metab* **90**, 1068–1071.
 197. Tentolouris N, Kokkinos A, Tsigos C, *et al.* (2004) Differential effects of high-fat and high-carbohydrate content isoenergetic meals on plasma active ghrelin concentrations in lean and obese women. *Horm Metab Res* **36**, 559–563.
 198. Lithander FE, Keogh GF, Wang Y, *et al.* (2008) No evidence of an effect of alterations in dietary fatty acids on fasting adiponectin over 3 weeks. *Obesity* **16**, 592–599.
 199. Sanchez J, Oliver P, Pico C, *et al.* (2004) Diurnal rhythms of leptin and ghrelin in the systemic circulation and in the gastric mucosa are related to food intake in rats. *Pflugers Arch* **448**, 500–506.
 200. Moesgaard SG, Ahren B, Carr RD, *et al.* (2004) Effects of high-fat feeding and fasting on ghrelin expression in the mouse stomach. *Regul Pept* **120**, 261–267.
 201. Perreault M, Istrate N, Wang L, *et al.* (2004) Resistance to the orexigenic effect of ghrelin in dietary-induced obesity in mice: reversal upon weight loss. *Int J Obes* **28**, 879–885.
 202. Liu X, York DA & Bray GA (2004) Regulation of ghrelin gene expression in stomach and feeding response to a ghrelin analogue in two strains of rats. *Peptides* **25**, 2171–2177.
 203. Beck B, Musse N & Stricker-Krongrad A (2002) Ghrelin, macronutrient intake and dietary preferences in Long–Evans rats. *Biochem Biophys Res Commun* **292**, 1031–1035.
 204. Greeley GH, Reed JT, Qi X, *et al.* (2007) Increased adiposity during high fat diet does not participate in suppression of stomach ghrelin production and secretion. *Gastroenterology* **132**, A586.
 205. Overduin J, Frayo RS, Grill HJ, *et al.* (2005) Role of the duodenum and macronutrient type in ghrelin regulation. *Endocrinology* **146**, 845–850.
 206. Sánchez J, Cladera MM, Llopis M, *et al.* (2010) The different satiating capacity of CHO and fats can be mediated by different effects on leptin and ghrelin systems. *Behav Brain Res* **124**, 183–188.
 207. Lichtenstein AH & Schwab US (2000) Relationship of dietary fat to glucose metabolism. *Atherosclerosis* **150**, 227–243.
 208. Riccardi G, Giacco R & Rivellese AA (2004) Dietary fat, insulin sensitivity and the metabolic syndrome. *Clin Nutr* **23**, 447–456.
 209. Bray GA, Lovejoy JC, Smith SR, *et al.* (2002) The influence of different fats and fatty acids on obesity, insulin resistance and inflammation. *J Nutr* **132**, 2488–2491.
 210. Lovejoy JC, Champagne CM, Smith SR, *et al.* (2001) Relationship of dietary fat and serum cholesterol ester and phospholipid fatty acids to markers of insulin resistance in men and women with a range of glucose tolerance. *Metab Clin Exp* **50**, 86–92.
 211. Vessby B, Uusitupa M, Hermansen K, *et al.* (2001) Substituting dietary saturated for monounsaturated fat impairs insulin sensitivity in healthy men and women: The KANWU study. *Diabetologia* **44**, 312–319.
 212. Barnard RJ, Roberts CK, Varon SM, *et al.* (1998) Diet-induced insulin resistance precedes other aspects of the metabolic syndrome. *J Appl Physiol* **84**, 1311–1315.
 213. Storlien LH, Higgins JA, Thomas TC, *et al.* (2000) Diet composition and insulin action in animal models. *Br J Nutr* **83**, S85–S90.
 214. Tsitouras PD, Gucciardo F, Salbe AD, *et al.* (2008) High omega-3 fat intake improves insulin sensitivity and reduces CRP and IL6, but does not affect other endocrine axes in healthy older adults. *Horm Metab Res* **40**, 199–205.
 215. Lombardo YB, Hein G & Chicco A (2007) Metabolic syndrome: effects of *n*-3 PUFAs on a model of dyslipidemia, insulin resistance and adiposity. *Lipids* **42**, 427–437.
 216. Toschke AM, Kuchenhoff H, Koletzko B, *et al.* (2005) Meal frequency and childhood obesity. *Obes Res* **13**, 1932–1938.
 217. Ma YS, Bertone ER, Stanek EJ, *et al.* (2003) Association between eating patterns and obesity in a free-living US adult population. *Am J Epidemiol* **158**, 85–92.
 218. De Castro JM (1995) Social facilitation of food intake in humans. *Appetite* **24**, 260.
 219. Herman CP, Roth DA & Polivy J (2003) Effects of the presence of others on food intake: a normative interpretation. *Psychol Bull* **129**, 873–886.
 220. Redd M & De Castro JM (1992) Social facilitation of eating: effects of social instruction on food intake. *Physiol Behav* **52**, 749–754.
 221. Brown KJ & Grunberg NE (1996) Effects of environmental conditions on food consumption in female and male rats. *Physiol Behav* **60**, 293–297.
 222. Feunekes GIJ, De Graaf C & Van Staveren WA (1995) Social facilitation of food intake is mediated by meal duration. *Physiol Behav* **58**, 551–558.
 223. Lopak V & Eikelboom R (2000) Pair housing induced feeding suppression: individual housing not novelty. *Physiol Behav* **71**, 329–333.
 224. Lopak V & Eikelboom R (2004) Modulation of the pair housing induced feeding suppression. *Physiol Behav* **83**, 157–164.
 225. O'Connor R & Eikelboom R (2000) The effects of changes in housing on feeding and wheel running. *Physiol Behav* **68**, 361–371.
 226. Perez C, Canal JR, Dominguez E, *et al.* (1997) Individual housing influences certain biochemical parameters in the rat. *Lab Anim* **31**, 357–361.
 227. Scalera G (1992) Taste preferences, body weight gain, food and fluid intake in singly or group-housed rats. *Physiol Behav* **52**, 935–943.

228. Sclafani A & Springer D (1976) Dietary obesity in adult rats – similarities to hypothalamic and human obesity syndromes. *Physiol Behav* **17**, 461–471.
229. Dallman MF, La Fleur SE, Pecoraro NC, *et al.* (2004) Minireview: glucocorticoids – food intake, abdominal obesity, and wealthy nations in 2004. *Endocrinology* **145**, 2633–2638.
230. Dallman MF, Pecoraro N, Akana SF, *et al.* (2003) Chronic stress and obesity: a new view of ‘comfort food’. *Proc Natl Acad Sci U S A* **100**, 11696–11701.
231. Torres SJ & Nowson CA (2007) Relationship between stress, eating behavior, and obesity. *Nutrition* **23**, 887–894.
232. Yeomans MR, Blundell JE & Leshem M (2004) Palatability: response to nutritional need or need-free stimulation of appetite? *Br J Nutr* **92**, S3–S14.
233. Yamaguchi S & Ninomiya K (2000) Umami and food palatability. *J Nutr* **130**, 921S–926S.
234. Swinburn BA & Ravussin E (1994) Energy and macronutrient metabolism. *Baillieres Clin Endocrinol Metab* **8**, 527–548.
235. LeBlanc J & Labrie A (1997) A possible role for palatability of the food in diet-induced thermogenesis. *Int J Obes* **21**, 1100–1103.
236. Holt SHA, Delargy HJ, Lawton CL, *et al.* (1999) The effects of high-carbohydrate vs high-fat breakfasts on feelings of fullness and alertness, and subsequent food intake. *Int J Food Sci Nutr* **50**, 13–28.
237. Sclafani A (2001) Post-ingestive positive controls of ingestive behavior. *Appetite* **36**, 79–83.
238. Warwick ZS, Schiffman SS & Anderson JJB (1990) Relationship of dietary fat content to food preferences in young rats. *Physiol Behav* **48**, 581–586.
239. Fushiki T & Kawai T (2005) Chemical reception of fats in the oral cavity and the mechanism of addiction to dietary fat. *Chem Senses* **30**, i184–i185.
240. Mizushige T, Inoue K & Fushiki T (2007) Why is fat so tasty? Chemical reception of fatty acid on the tongue. *J Nutr Sci Vitaminol* **53**, 1–4.
241. Gilbertson TA, Fontenot DT, Liu LD, *et al.* (1997) Fatty acid modulation of K⁺ channels in taste receptor cells: gustatory cues for dietary fat. *Am J Physiol Cell Physiol* **272**, C1203–C1210.
242. Mattes RD (2005) Fat taste and lipid metabolism in humans. *Physiol Behav* **86**, 691–697.
243. Fabry P, Hejda S, Cerny K, *et al.* (1966) Effect of meal frequency in schoolchildren. Changes in weight-height proportion and skinfold thickness. *Am J Clin Nutr* **18**, 358–361.
244. Bertéus Forslund H, Lindroos AK, Sjöström L, *et al.* (2002) Meal patterns and obesity in Swedish women – a simple instrument describing usual meal types, frequency and temporal distribution. *Eur J Clin Nutr* **56**, 740–747.
245. Andersson I & Rössner S (1996) Meal patterns in obese and normal weight men: the ‘Gustaf’ study. *Eur J Clin Nutr* **50**, 639–646.
246. Qin LQ, Li J, Wang Y, *et al.* (2003) The effects of nocturnal life on endocrine circadian patterns in healthy adults. *Life Sci* **73**, 2467–2475.
247. Kant AK, Schatzkin A & Ballard-Barbash R (1997) Evening eating and subsequent long-term weight change in a national cohort. *Int J Obes* **21**, 407–412.
248. Taylor E, Missik E, Hurley R, *et al.* (2004) Obesity treatment: broadening our perspective. *Am J Health Behav* **28**, 242–249.
249. Bellisle F (2004) Impact of the daily meal pattern on energy balance. *Scand J Nutr Naringsforsk* **48**, 114–118.
250. LeMagnen J & Devos M (1970) Metabolic correlates of meal onset in free food intake of rats. *Physiol Behav* **5**, 805–814.
251. Clifton PG (2000) Meal patterning in rodents: psychopharmacological and neuroanatomical studies. *Neurosci Biobehav Rev* **24**, 213–222.
252. Prins AA, Dejongnagelsmit A, Keijser J, *et al.* (1986) Daily rhythms of feeding in the genetically-obese and lean Zucker rats. *Physiol Behav* **38**, 423–426.
253. LeMagnen J (1988) Lipogenesis, lipolysis and feeding rhythms. *Ann Endocrinol (Paris)* **49**, 98–104.
254. Becker EE & Grinker JA (1977) Meal patterns in genetically obese Zucker rat. *Physiol Behav* **18**, 685–692.
255. Fukagawa K, Sakata T, Yoshimatsu H, *et al.* (1992) Advance shift of feeding circadian-rhythm induced by obesity progression in Zucker rats. *Am J Physiol* **263**, R1169–R1175.
256. Ho A & Chin A (1988) Circadian feeding and drinking patterns of genetically-obese mice fed solid chow diet. *Physiol Behav* **43**, 651–656.
257. Strohmayr AJ & Smith GP (1987) The meal pattern of genetically-obese (ob ob) mice. *Appetite* **8**, 111–123.
258. Drewnowski A, Cohen AE, Faust IM, *et al.* (1984) Meal-taking behavior is related to predisposition to dietary obesity in the rat. *Physiol Behav* **32**, 61–67.
259. Farley C, Cook JA, Spar BD, *et al.* (2003) Meal pattern analysis of diet-induced obesity in susceptible and resistant rats. *Obes Res* **11**, 845–851.
260. Cottone P, Sabino V, Nagy TR, *et al.* (2007) Feeding microstructure in diet-induced obesity susceptible versus resistant rats: central effects of urocortin 2. *J Physiol (London)* **583**, 487–504.
261. Paulino G, Darcel N, Tome D, *et al.* (2008) Adaptation of lipid-induced satiation is not dependent on caloric density in rats. *Physiol Behav* **93**, 930–936.
262. Synowski SJ, Smart AB & Warwick ZS (2005) Meal size of high-fat food is reliably greater than high-carbohydrate food across externally-evoked single-meal tests and long-term spontaneous feeding in rat. *Appetite* **45**, 191–194.
263. Mistlberger RE, Lukman H & Nadeau BG (1998) Circadian rhythms in the Zucker obese rat: assessment and intervention. *Appetite* **30**, 255–267.
264. Thibault L & Booth DA (1999) Macronutrient-specific dietary selection in rodents and its neural bases. *Neurosci Biobehav Rev* **23**, 457–528.
265. Branth S, Ronquist G, Stridsberg M, *et al.* (2007) Development of abdominal fat and incipient metabolic syndrome in young healthy men exposed to long-term stress. *Nutr Metab Cardiovasc Dis* **17**, 427–435.
266. Laitinen J, Ek E & Sovio U (2002) Stress-related eating and drinking behavior and body mass index and predictors of this behavior. *Prev Med* **34**, 29–39.
267. Rivenes AC, Harvey SB & Mykletun A (2009) The relationship between abdominal fat, obesity, and common mental disorders: results from the HUNT Study. *J Psychosom Res* **66**, 269–275.
268. Zhao G, Ford ES, Dhingra S, *et al.* (2009) Depression and anxiety among US adults: associations with body mass index. *Int J Obes* **33**, 257–266.
269. Allison DB, Newcomer JW, Dunn AL, *et al.* (2009) Obesity among those with mental disorders. A National Institute of Mental Health meeting report. *Am J Prev Med* **36**, 341–350.
270. Pecoraro N, Reyes F, Gomez F, *et al.* (2004) Chronic stress promotes palatable feeding, which reduces signs of stress: feedforward and feedback effects of chronic stress. *Endocrinology* **145**, 3754–3762.
271. Oliver G & Wardle J (1999) Perceived effects of stress on food choice. *Physiol Behav* **66**, 511–515.

272. Levin BE, Richard D, Michel C, *et al.* (2000) Differential stress responsivity in diet-induced obese and resistant rats. *Am J Physiol Regul Integr Comp Physiol* **279**, R1357–R1364.
273. Marti O, Marti J & Armario A (1994) Effects of chronic stress on food intake in rats: influence of stressor intensity and duration of daily exposure. *Physiol Behav* **55**, 747–753.
274. Rowland NE & Antelman SM (1976) Stress-induced hyperphagia and obesity in rats: a possible model for understanding human obesity. *Science* **191**, 310–312.
275. Legendre A & Harris RBS (2006) Exaggerated response to mild stress in rats fed high-fat diet. *Am J Physiol Regul Integr Comp Physiol* **291**, R1288–R1294.
276. Tamashiro KKK, Hegeman MA & Sakai RR (2006) Chronic social stress in a changing dietary environment. *Physiol Behav* **89**, 536–542.
277. Teegarden SL & Bale TL (2008) Effects of stress on dietary preference and intake are dependent on access and stress sensitivity. *Physiol Behav* **93**, 713–723.
278. Adam TC & Epel ES (2007) Stress, eating and the reward system. *Physiol Behav* **91**, 449–458.
279. Ochi M, Tominaga K, Tanaka F, *et al.* (2008) Effect of chronic stress on gastric emptying and plasma ghrelin levels in rats. *Life Sci* **82**, 862–868.
280. Kristensson E, Sundqvist M, Astin M, *et al.* (2006) Acute psychological stress raises plasma ghrelin in the rat. *Regul Pept* **134**, 114–117.
281. Karnehed N, Tynelius P, Heitmann BL, *et al.* (2006) Physical activity, diet and gene–environment interactions in relation to body mass index and waist circumference: the Swedish Young Male Twins Study. *Public Health Nutr* **9**, 851–858.
282. Marrades MP, Martinez JA & Moreno-Aliaga MJ (2007) Differences in short-term metabolic responses to a lipid load in lean (resistant) vs obese (susceptible) young male subjects with habitual high-fat consumption. *Eur J Clin Nutr* **61**, 166–174.
283. Speechly DP & Buffenstein R (2000) Appetite dysfunction in obese males: evidence for role of hyperinsulinaemia in passive overconsumption with a high fat diet. *Eur J Clin Nutr* **54**, 225–233.
284. Levin BE, Dunn-Meynell AA, McMinin JE, *et al.* (2003) A new obesity-prone, glucose-intolerant rat strain (f.Dio). *Am J Physiol Regul Integr Comp Physiol* **285**, R1184–R1191.
285. Commerford SR, Pagliassotti MJ, Melby CL, *et al.* (2000) Fat oxidation, lipolysis, and free fatty acid cycling in obesity-prone and obesity-resistant rats. *Am J Physiol Endocrinol Metab* **279**, E875–E885.
286. Commerford SR, Pagliassotti MJ, Melby CL, *et al.* (2001) Inherent capacity for lipogenesis or dietary fat retention is not increased in obesity-prone rats. *Am J Physiol Regul Integr Comp Physiol* **280**, R1680–R1687.
287. Abdoulaye D, Wetzler S, Goubern M, *et al.* (2006) Comparison of energy balance in two inbred strains of rats: Fischer F344 prone to obesity and Lou rats resistant to obesity. *Physiol Behav* **87**, 245–250.
288. Levin BE & Dunn-Meynell AA (2000) Defense of body weight against chronic caloric restriction in obesity-prone and -resistant rats. *Am J Physiol Regul Integr Comp Physiol* **278**, R231–R237.
289. Jackman MR, Kramer RE, MacLean PS, *et al.* (2006) Trafficking of dietary fat in obesity-prone and obesity-resistant rats. *Am J Physiol-Endocrinol Metab* **291**, E1083–E1091.
290. Pagliassotti MJ, Knobel SM, Shahrokhi KA, *et al.* (1994) Time-course of adaptation to a high-fat diet in obesity-resistant and obesity-prone rats. *Am J Physiol* **267**, R659–R664.
291. Levin BE & Dunn-Meynell AA (1997) Dysregulation of arcuate nucleus preproenkephalin Y mRNA in diet-induced obese rats. *Am J Physiol Regul Integr Comp Physiol* **272**, R1365–R1370.
292. Levin BE (1995) Reduced norepinephrine turnover in organs and brains of obesity-prone rats. *Am J Physiol Regul Integr Comp Physiol* **268**, R389–R394.
293. Blaak E (2001) Gender differences in fat metabolism. *Curr Opin Clin Nutr Metab Care* **4**, 499–502.
294. Power ML & Schulkin J (2008) Sex differences in fat storage, fat metabolism, and the health risks from obesity: possible evolutionary origins. *Br J Nutr* **99**, 931–940.
295. Sweeting HN (2008) Gendered dimensions of obesity in childhood and adolescence. *Nutr J* (publication 14 January 2008).
296. Geary N (2004) Is the control of fat ingestion sexually differentiated? *Physiol Behav* **83**, 659–671.
297. Charles River Laboratories (2006) Research models and services. http://www.criver.com/flex_content_area/documents/rm_rm_c_sprague_dawley_rats.pdf (accessed February 2009)
298. Mayes JS & Watson GH (2004) Direct effect of sex steroid hormones on adipose tissues and obesity. *Obes Rev* **5**, 197–216.
299. Rodríguez AM, Quevedo-Coli S, Roca P, *et al.* (2001) Sex-dependent dietary obesity, induction of UCPs, and leptin expression in rat adipose tissues. *Obes Res* **9**, 579–588.
300. Gayle DA, Desai M, Casillas E, *et al.* (2006) Gender-specific orexigenic and anorexigenic mechanisms in rats. *Life Sci* **79**, 1531–1536.
301. Andersen ME, Clewell HJ, Gearhart J, *et al.* (1997) Pharmacodynamic model of the rat estrus cycle in relation to endocrine disruptors. *J Toxicol Environ Health* **52**, 189–209.
302. Hill JO, Dorton J, Sykes MN, *et al.* (1989) Reversal of dietary obesity is influenced by its duration and severity. *Int J Obes* **13**, 711–722.
303. Parekh PI, Petro AE, Tiller JM, *et al.* (1998) Reversal of diet-induced obesity and diabetes in C57BL/6J mice. *Metab Clin Exp* **47**, 1089–1096.
304. Wade GN (1983) Dietary obesity in golden hamsters: reversibility and effects of sex and photoperiod. *Physiol Behav* **30**, 131–137.
305. Levin BE & Keeseey RE (1998) Defense of differing body weight set points in diet-induced obese and resistant rats. *Am J Physiol Regul Integr Comp Physiol* **274**, R412–R419.
306. Miller WH Jr, Faust IM, Goldberger AC, *et al.* (1983) Effects of severe long-term food deprivation and refeeding on adipose tissue cells in the rat. *Am J Physiol Endocrinol Metab* **8**, E74–E80.
307. Yang MU, Presta E & Bjorntorp P (1990) Refeeding after fasting in rats: effects of duration of starvation and refeeding on food efficiency in diet-induced obesity. *Am J Clin Nutr* **51**, 970–978.
308. Shi H, Akunuru S, Bierman JC, *et al.* (2009) Diet-induced obese mice are leptin insufficient after weight reduction. *Obesity* **17**, 1702–1709.
309. Gullicksen PS, Hausman DB, Dean RG, *et al.* (2003) Adipose tissue cellularity and apoptosis after intracerebroventricular injections of leptin and 21 days of recovery in rats. *Int J Obes* **27**, 302–312.
310. Qian H, Azain MJ, Hartzell DL, *et al.* (1998) Increased leptin resistance as rats grow to maturity. *Proc Soc Exp Biol Med* **219**, 160–165.