Effects of dietary fat and carbohydrate on appetite vary depending upon site and structure

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The present review summarises the effects of different carbohydrate and fat structures on food intake and appetite and the differences in response at various levels of processing of macronutrients. Several physico-chemical properties of carbohydrate and fat molecules appear to influence the short-term satiating properties. However, long-term substantiation of these findings expressed in terms of food intake or body weight is not currently available. Such studies will be required to make clear recommendations regarding dietary composition to aid satiety.

Fat: Carbohydrate: Appetite

The physiological regulation of food intake and appetite involves a complex series of signals emanating from the gastrointestinal tract, liver and adipose stores, as well as centrally generated hunger and satiety signals. Given the epidemiological evidence that a high fat intake tends to lead to a higher body weight, a great deal of research has been conducted to investigate the relative effects of fat and carbohydrate on appetite and food intake. As the physiological processing systems involved in the ingestion, digestion, absorption and metabolism of foods are complex, it is not surprising that there are subtle differences associated with these macronutrients in terms of their subsequent satiating effects. The present review will attempt to summarise the effects of different carbohydrate and fat structures on food intake and appetite and the differences in response at various levels of processing of macronutrients.

Oral preloading studies: fat *v*. carbohydrate

The standard methodology used in this area of research is that of oral preloading, whereby a covertly manipulated food or drink is given at a predetermined time before ingestion of an *ad libitum* test meal. Using this technique, the influence of fat and carbohydrate on subsequent intake have been widely tested. Many studies have indicated that fat is less satiating than carbohydrate and it has been thus suggested that fat may lead to passive over-consumption (Blundell *et al.* 1993). However, there have been a number of studies that do not support this contention, particularly when preloads have been matched for energy density and palatability (Geliebter, 1979). It appears that energy density is the key driver of satiety in these

controlled conditions; there may be smaller individual effects of macronutrients and/or specific chemical differences that may provide useful insight into the regulation of intake and specific strategies that could be employed to manipulate satiety (Raben *et al.* 2003).

Many different carbohydrate molecules have been utilised in these studies: glucose; maltose; fructose; sucrose; maltodextrin. Similarly, a wide variety of oils and fats have been compared in this type of study (maize oil, Intralipid (commercially available lipid emulsion), SCFA, medium- and long-chain fatty acids, saturated and unsaturated fatty acids). Therefore, direct comparison between studies is difficult; however, it is clear that not all carbohydrates or fats act the same on appetite or the associated physiological processes. Some of the major classifications that can be taken from this wide literature follow.

Carbohydrates

Simple sugars

A wide variety of simple sugars have been utilised in tests of feeding behaviour. Ingested carbohydrates are digested and absorbed as simple monosaccharides or disaccharides and utilised or stored in the body as glucose (or polymers of glucose). Hence, the common monosaccharide molecules, glucose and fructose, have been widely used as sugar molecules in feeding behaviour studies. A large number of studies have demonstrated a compensatory response at an *ad libitum* feeding test to ingestion of a preload of monosaccharides or disaccharides when compared with a non-nutritive sweetened control drink or added to a test food (Rogers *et al.* 1988; Lavin *et al.*

1997). It should be noted, however, that not all studies have demonstrated a compensation for sugar ingestion and in some cases a stimulation of intake has been observed (e.g. Spitzer & Rodin, 1987). As will be discussed, considering the wide differences in physiological response and methodological differences employed (for review of methodologies, see Reid & Hetherington, 1997), it is not surprising that differences in feeding effect are found.

Glucose v. fructose

Glucose and fructose are the two major monosaccharides and principal components of available sugars; thus, the comparison of glucose and fructose has been of wide interest in terms of appetite regulation and subsequent physiological responses. This area is becoming increasingly of interest as some studies have suggested that increased fructose consumption may be associated with weight gain. Contrary to this argument, however, a number of studies have shown that fructose reduces appetite and food intake to a greater extent than glucose (Spitzer & Rodin, 1987; Rayner *et al.* 2000). One study, however, has shown no difference in appetite or food intake between fructose and glucose (Kong *et al.* 1999).

Gastric emptying rate of fructose is more rapid than glucose (Guss *et al.* 1994) and insulin release is lower following fructose ingestion in human subjects (MacDonald *et al.* 1978). These differences are probably related to the specific intestinal transporter mechanisms for fructose and glucose (Levin, 1994). The response to glucose and fructose seems to depend upon site of administration, as Kong *et al.* (1999) showed that oral fructose was less effective in stimulating the putative satiety hormone, glucagon-like peptide-1, whilst having similar effects on appetite and subsequent food intake. Rayner *et al.* (2000) demonstrated, on the other hand, that intraduodenal infusion of fructose reduces subsequent food intake to a greater extent than glucose, whilst having a similar stimulatory effect on glucagon-like peptide-1. These differences are difficult to explain purely in terms of gastric delivery differences in the oral condition, as it would be expected that fructose would empty more quickly and may reduce appetite (at least in the short term) more strongly than glucose and raise glucagon-like peptide-1 concentrations more strongly.

The faster gastric emptying and lower insulin response of fructose are also observed when it is incorporated into the disaccharide sucrose (glucose–fructose) when compared with maltose (glucose–glucose). Despite the differences in gastric emptying, appetite responses to sucrose and maltose have been shown to be similar (Lavin *et al.* 2002).

Polysaccharides

The major current area of interest concerning the role of polysaccharides and satiety relates to the glycaemic index (GI) of carbohydrate-containing products. GI relates to the speed at which a fixed amount (usually 75 or 50 g) of ingested carbohydrate source raises blood glucose over a fixed time period (2 or 3 h), expressed as a percentage of a reference blood glucose response (to glucose or white bread consumption; Jenkins *et al.* 1981). A great deal of work has been carried out to investigate the relationship between blood glucose or its utilisation and hunger and food intake (Campfield, 1997; Melanson *et al.* 1999). Hence, as the use of GI has become more widespread, its role in determining the satiety response has been investigated. There is still a great deal of controversy on the long-term influence of a low-GI diet on body weight and there is a general call for randomised, controlled intervention trials in this area. However, several short-term studies have been conducted that have investigated the role of the GI of test foods on subsequent appetite and food intake. In a recent review (Raben, 2002) of thirty-one short-term studies, fifteen studies demonstrated that low-GI foods reduce hunger or increase satiety, fourteen found no effect and two actually found lower satiety following the low-GI test compared with the high-GI test. As with many areas of research, a wide variety of methodologies have been employed, making a systematic analysis of the key factors potentially accounting for differences difficult. Certainly, the physiological profile of low-GI diets (slower gastric emptying, digestion and absorption, lower peak insulin and glucose followed by slower declines and less severe nadirs in glucose levels) would fit with scientific knowledge concerning appetite suppression (Pawlak *et al.* 2002). Further well-controlled, appropriately powered, randomised intervention trials are needed to critically address this question (Astrup, 2002).

Fats

Three major areas associated with fat structure have been investigated with regard to their satiating effectiveness. Chain length and degree of saturation of fats have a large impact on their physico-chemical properties and several studies have investigated the role of these factors on appetite and eating behaviour. The final area that has received some attention relates to the functionality of specific fat molecules, particularly conjugated linoleic acid (CLA), mainly in terms of weight regulation and metabolism, but also recently on food intake and appetite.

Chain length

Medium-chain triacylglycerols (MCT) are hydrolysed and absorbed more rapidly than long-chain triacylglycerols. MCT are hydrolysed to medium-chain fatty acids, which are directly absorbed into the portal system, whereas long-chain triacylglycerols are transported in chylomicrons and through the lymphatic system. In addition, MCT are preferentially oxidised and are able to cross the inner mitochondrial membrane independently of acylcarnitine transferase (Bremer, 1983); increases in fatty acid oxidation in the liver has itself been proposed as a satiety signal (Langhans, 1996).

A number of studies have shown MCT to be more satiating than long-chain triacylglycerols in both animals and

human subjects (Stubbs & Harbron 1996; Wymelbeke *et al.* 1998). Furthermore, MCT added to a very-low energy diet have been shown to speed the rate of weight loss and enhance satiety in the first 2 weeks of weight loss (Krotkiewski, 2001). Within the range of MCT, it has previously been demonstrated that longer-chain-length molecules lead to a greater inhibition of food intake in rats (McCaffery *et al.* 1994). Chain length of fatty acids also appears critical for cholecystokinin release with a cut-off point of C_{12}, below which there appears to be no release (McLaughlin *et al.* 1999).

Saturation

The influence of the degree of saturation of the fatty acid molecules (either as salts of the fatty acids or as oils/emulsions) upon appetite and food intake has been tested in both animals and more recently in human subjects. The degree of saturation influences a number of the physico-chemical properties of the oil (e.g. melting point) as well as the rate of digestion and absorption (Small, 1991).

Within the C_{18} fatty acids, linoleic acid was found to be more satiating when infused into the upper small intestine in human subjects than oleic or stearic acids (French *et al.* 2000). Similar findings have been noted when oils are incorporated into foods (Lawton *et al.* 2000). These findings may relate to the speed of processing of the different oils and possibly to the neurochemical responses evoked following ingestion. Cholecystokinin has previously been shown to be more potently released following linoleic acid-containing oils compared with other long-chain fatty acid-containing oils (Beardshall *et al.* 1989). ApoA-IV release is also more potently released by linoleic acid in rats (Kalogeris *et al.* 1996). Both of these gastrointestinal chemicals have been shown to induce satiety (Fujimoto *et al.* 1992; Ballinger *et al.* 1995).

Conjugated linoleic acid

CLA has recently been implicated with a number of potential health benefits. Several studies have recently been carried out in human subjects to investigate the effects of CLA supplementation on measures of obesity. These studies have shown that daily intake of CLA can reduce total body fat (Blankson *et al.* 2000) or abdominal fat (Riserus *et al.* 2001). In addition, two studies have also shown significant reductions (Medina *et al.* 2000) or inverse associations (Belury *et al.* 2003) with circulating leptin levels. Of these studies, however, only one has attempted to assess appetite effects of CLA in human subjects without significant findings (Medina *et al.* 2000).

Summary

Several physico-chemical properties of carbohydrate and fat molecules appear to influence the short-term satiating properties. However, long-term substantiation of these findings expressed either in terms of food intake or body weight is not currently available. Such studies will be required to make clear recommendations regarding dietary composition to aid satiety.

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