Impact of inulin and oligofructose on gastrointestinal peptides

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In the present paper, we summarise the data supporting the following hypothesis: dietary inulin-type fructans extracted from chicory root may modulate the production of peptides, such as incretins, by endocrine cells present in the intestinal mucosa, this phenomenon being involved in the regulation of food intake and/or systemic effects. To test this hypothesis, male Wistar rats received for 3 weeks either a standard diet or the same diet supplemented with 10% inulin-type fructans with different degrees of polymerisation. All the effects were most pronounced with the diet containing oligofructose, and consisted of (i) a decrease in mean daily energy intake and in epidydimal fat mass; (ii) a higher caecal pool of the anorexigenic glucagon-like peptide-1 (7–36) amide (GLP-1), and peptide YY (PYY), due to caecal tissue proliferation; (iii) an increase in GLP-1 and of its precursor – proglucagon mRNA – concentrations in the proximal colon; (iv) an increase in portal serum level of GLP-1 and PYY; (v) a decrease in serum orexigenic peptide ghrelin. Moreover, oligofructose supplementation improved glucose homeostasis (i.e. decreased glycaemia, increased pancreatic and serum insulin content) in diabetic rats previously treated with streptozotocin, a phenomenon that is partly linked to the reduction in food intake and that correlates with the increase in colic and portal GLP-1 content. Based on these results it appears justified to test, in human subjects, the hypothesis that dietary inulin-type fructans could play a role in the management of obesity and diabetes through their capacity to promote secretion of endogenous gastrointestinal peptides involved in appetite regulation.

Oligofructose: Glucagon-like peptide-1: Peptide YY: Ghrelin: Rats

Inulin-type fructans have recently been recognised as interesting dietary fibres, not only able to improve intestinal functions through their prebiotic properties but also to exert beneficial systemic effects (Roberfroid & Delzenne, 1998; Delzenne, 2003).

In our laboratory, we have shown that the addition of inulin-type fructans at the dose of 10% (w/w) in the diet for several weeks decreases triacylglycerol accumulation in the liver and epididyimal fat mass, both in normal and obese Zucker fa/fa rats (Daubioul et al. 2000, 2002). In the normal rat, this effect is linked to a decrease in hepatic lipogenesis and a decrease in postprandial triglyceridaemia (Delzenne & Kok, 2001). In obese rats, the administration of oligofructose (for the description of the different inulin-type fructans, see the paper by Roberfroid in this supplement), and also of oligofructose-enriched inulin is clearly responsible for an improvement of steatosis (Daubioul et al. 2002). Most of the effects of inulin-type fructans on lipid metabolism correlated with a decrease in food-derived energy intake, mainly due to a lower calorific value of the fructans-containing diet. Normally, rats compensate for the lower calorific value of the diet by increasing the daily amount of ingested diet: in the Zucker rat, the addition of 10% cellulose in the diet did not protect rats against steatosis because cellulose-treated rats ate about 10% more diet per day during the treatment (Daubioul et al. 2002). This led us to postulate that the addition of inulin-type fructans was able to help reduce food intake – and subsequently fat mass development – in animals. However, a fundamental question remains to be answered: how do, from a mechanistic point of view, non-digestible/fermentable fibres, such as inulin-type fructans, exert a satiating effect?

Involvement of gastrointestinal peptides in the regulation of food intake by dietary inulin-type fructans: from theory to experimental data

Endocrine cells present in the intestinal mucosa secrete peptides involved in the regulation of food intake and/or pancreatic functions – the latter being called incretins (Drue et al. 2004; Stanley et al. 2004). Endocrine L-cells are distributed all along the intestinal tract and are also mostly present in the caeco-colon, where fermentation of inulin-type fructans occurs (Drucker, 2002). L-cells secrete several peptides, derived from the expression of the proglucagon gene, followed by the selective cleavage of the peptide through the action of pro-hormone convertase 1/3; post-translational modification leads to the production of glucagon-like peptide-1 (7–36) amide (GLP-1), GLP-2, oxyntomodulin, glicentin and intervening peptide-2 (Drucker, 2002; Stanley et al. 2004). L-cells also produce peptide YY (1–36) amide from the PYY gene, this peptide being cleaved by dipeptidylpeptidase IV into PYY (3–36) amide (PYY).

Among those peptides, GLP-1, oxyntomodulin and PYY have recently been proposed as important modulators of appetite through their peripheral effect (vagal nerve) and/or by acting directly on the arcuate nucleus (Drue et al. 2004; Stanley et al. 2004). GLP-1 is also involved in the regulation of pancreatic

Abbreviations: GLP-1, glucagon-like peptide-1; STZ, streptozotocin; PYY, peptide YY.

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secretion of insulin and in the differentiation and maturation of β-cells (Brubaker & Drucker, 2004).

The facts that:

(1) those peptides are mainly produced in the lower part of the gut, where non-digestible oligosaccharides including inulin-type fructans are largely fermented,

(2) the products of such a fermentation in the gut – namely, SCFA – are known to increase the expression of proglucagon in the intestinal tissue (Tappenden et al. 1998; Drozdowski et al. 2002) and

(3) some dietary fibres are able to increase proglucagon expression when given at high doses in the diet of dogs or rats (Reimer & McBurney, 1996; Massimino et al. 1998),

led us to verify the production of gut peptides in the different segments of the intestine of rats receiving inulin-type fructans in their diet. Subsequently, we also correlated incretin production with the modulation of food intake, fat mass development, and, in a model of diabetic rats, we assessed parameter markers of the pancreatic function.

Effects of inulin-type fructans in normal rats

We first compared the influence of inulin-type fructans with different degrees of polymerisation, namely oligofructose, oligofructose-enriched inulin and high-molecular-weight inulin, on GLP-1 and PYY production. The concentration of these peptides, and of the corresponding mRNA precursor, was measured in the different segments of the intestinal tract in male Wistar rats and of the corresponding mRNA precursor, was measured in the different segments of the intestinal tract in male Wistar rats. The results obtained in normal rats demonstrated that oligofructose was the most potent inulin-type fructan in terms of GLP-1 production in the intestinal tissue. GLP-1 (7–36) amide is considered a key peptide in the control of glucose-dependent insulin release by pancreatic β-cells. Moreover, it is also responsible for an increased β-cells neogenesis in streptozotocin (STZ)-treated newborn rats – a model of diabetes – thus allowing a partial recuperation of pancreatic function with age (Tourrel et al. 2001).

We decided to investigate the effects of oligofructose feeding in growing rats treated with intravenous injection of STZ at a dose of 30 mg/kg bodyweight. The results obtained in normal rats demonstrated that oligofructose was the most potent inulin-type fructan in terms of GLP-1 production in the intestinal tissue. GLP-1 (7–36) amide is considered a key peptide in the control of glucose-dependent insulin release by pancreatic β-cells. Moreover, it is also responsible for an increased β-cells neogenesis in streptozotocin (STZ)-treated newborn rats – a model of diabetes – thus allowing a partial recuperation of pancreatic function with age (Tourrel et al. 2001).

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et al. in the pancreatic tissue, as well as postprandial insulinaemia (Cani et al. 2004).

This is in accordance with the results of Nie et al. (2000), suggesting that the increase in GLP-1 in the pancreatic tissue of STZ-treated rats was rather due to an increase in pro-hormone convertase 1/3 activity than to a modulation of proglucagon expression. Both colic and portal concentration of GLP-1 were increased in STZ animals, but to a greater extent in oligofructose-treated rats than in rats receiving the standard diet (Table 2). From those experiments, we may suggest that the presence of oligofructose in the diet of rats previously treated with STZ improves glucose homeostasis (decrease in glycaemia, increase in pancreatic and serum insulin), a phenomenon partially dependent on food restriction. The involvement of colonic GLP-1 in the effects is likely, even if diabetic rats fed a standard diet also exhibit a higher intestinal GLP-1 content. This latter effect could be seen as a putative ‘compensatory’ mechanism that might be amplified (or accelerated?) by oligofructose. A recent study has also tested the influence of oligofructose in another model of diabetes (type 1 diabetes mellitus induced by dietary proteins in the diabetes-prone BB rat; Perrin et al. 2003). The authors have shown that at the concentration of 5% in the diet, oligofructose did not modify, when compared to cellulose, the incidence of pancreatic alterations. The dose of oligofructose as well as the origin of the alteration of pancreatic cells (autoimmune disease in the prone diabetic rats) is different, a fact that might explain the discrepancies between results. However, we may also postulate that the effectiveness of the oligofructose treatment may depend on its satiating effect, and on its effect on incretins production, which has not been reported in other studies. These could be key parameters to measure in the future.

Further studies are needed to assess the implication of GLP-1 on the effects of oligofructose, i.e. by analysing its influence on GLP-1 receptors in knockout mice (Burcelin et al. 2001).

Conclusions and perspectives: from the molecular basis towards human health

Figure 2 summarises the effects of oligofructose on intestinal incretins based on our data. In conclusion, we confirm that oligofructose in the diet of rats increases the availability of GLP-1 coming from the caeco-colon. The molecular mechanism remains to be fully elucidated, but in view of our data we propose that an increased production of the precursor proglucagon mRNA is a key event. Recent papers, based both on in vitro and in vivo studies in animals, suggest a role of SCFA in the regulation of the expression of the intestinal proglucagon gene (Tappenden et al. 1998; Drozdowski et al. 2002). Since fermentation of oligofructose and of other non-digestible/fermentable carbohydrates, such as resistant starch or galactooligosaccharides, produces a specific profile of SCFA, it would be interesting to correlate the pattern of fermentation in situ with the increase in incretin expression.

Table 1. Portal glucagon-like peptide-1 (7–36) amide (GLP-1) and peptide YY (3–36) (PYY) amide concentrations of rats fed a control diet (CT) or a diet supplemented with oligofructose (OFS), oligofructose-enriched inulin (Syn) or high-molecular-weight inulin (Inu) (adapted from Cani et al. 2004) (Mean values and standard errors of the mean for six animals per group)

<table>
<thead>
<tr>
<th></th>
<th>Portal vein peptides</th>
<th>GLP-1 (7–36) amide (pmol/g)</th>
<th>PYY (3–36) amide (pg/ml)</th>
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<tbody>
<tr>
<td></td>
<td>Mean (SEM)</td>
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<td></td>
</tr>
<tr>
<td>CT</td>
<td>7·8a (0·7)</td>
<td>42·7a (8·2)</td>
<td></td>
</tr>
<tr>
<td>OFS</td>
<td>11·4a (1·2)</td>
<td>84·9b (10·3)</td>
<td></td>
</tr>
<tr>
<td>Syn</td>
<td>10·5a (1·7)</td>
<td>55·7a (11·0)</td>
<td></td>
</tr>
<tr>
<td>Inu</td>
<td>8·4a (1·3)</td>
<td>48·3a (13·9)</td>
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Table 2. Concentration of glucagon-like peptide-1 (7–36) amide (GLP-1) in the portal vein, ileal and colonic intestinal segments in control (CT) rats, streptozotocin-treated control (STZ-CT) rats, streptozotocin-treated rats receiving a 10% oligofructose diet (STZ-OFS) and streptozotocin-treated food-restricted (STZ-Res) rats (Mean values and standard errors of the mean for five animals per group)

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<td></td>
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</tr>
<tr>
<td>CT</td>
<td>10·04 (0·45)</td>
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<tr>
<td>STZ-CT</td>
<td>26·4* (4·25)</td>
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30–40 mg/kg body weight. The results are submitted for publication and can be summarised as follows: 1 week after the STZ treatment, rats were selected based on their glycaemia (between 15 and 35 mm), and randomised into three experimental groups, namely:

(1) An STZ-control group, receiving the standard A04 diet;
(2) An STZ-OFS group, receiving a diet containing 10% oligofructose;
(3) An STZ-restriction group that was food-restricted in order to receive the same amount of diet compared to the non-diabetic animals (treated with citrate in place of STZ, and receiving the control A04 diet throughout the treatment).

Oligofructose treatment reduced, to a large extent, all symptoms associated with diabetic state (postprandial hyperglycaemia, hyperphagia, polydypsia, weight loss) normally observed in STZ-treated animals (Cani et al. 2004b). The drastic dietary restriction only partially explains the improvement of glycaemia in those conditions. Interestingly, a prolonged oligofructose treatment (6 weeks) allows a partial restoration of the pancreatic insulin content and brings back to normal percentage values of β-cells in the pancreatic tissue, as well as postprandial insulinemia (Cani et al. 2004b). Since oligofructose treatment was able to both reduce food intake and improve glucose metabolism in STZ-diabetic rats, we have analysed GLP-1 content in the different parts of the intestine and in the portal vein of the animals (Table 2). Surprisingly, 4 weeks after STZ injection, the ileal concentration of GLP-1 was higher in rats receiving the standard diet than in rats receiving the diet containing oligofructose, or food-restricted.

This would mean that hyperphagia, and consequently, the large amount of nutrients reaching the gut, increase the GLP-1 content in the ileal tissue; however, no modification of proglucagon mRNAs content was observed (data not shown), thus leading us to postulate that the mechanism of the ileal overproduction of GLP-1 in diabetic rats is not due to an increase in gene expression. This is in accordance with the results of Nie et al. (2000), suggesting that the increase in GLP-1 in the pancreatic tissue of STZ-treated rats was rather due to an increase in pro-hormone convertase 1/3 activity than to a modulation of proglucagon expression. Both colic and portal concentration of GLP-1 were increased in STZ animals, but to a greater extent in oligofructose-treated rats than in rats receiving the standard diet (Table 2). From those experiments, we may suggest that the presence of oligofructose in the diet of rats previously treated with STZ improves glucose homeostasis (decrease in glycaemia, increase in pancreatic and serum insulin), a phenomenon partially dependent on food restriction. The involvement of colonic GLP-1 in the effects is likely, even if diabetic rats fed a standard diet also exhibit a higher intestinal GLP-1 content. This latter effect could be seen as a putative ‘compensatory’ mechanism that might be amplified (or accelerated?) by oligofructose. A recent study has also tested the influence of oligofructose in another model of diabetes (type 1 diabetes mellitus induced by dietary proteins in the diabetes-prone BB rat; Perrin et al. 2003). The authors have shown that at the concentration of 5% in the diet, oligofructose did not modify, when compared to cellulose, the incidence of pancreatic alterations. The dose of oligofructose as well as the origin of the alteration of pancreatic cells (autoimmune disease in the prone diabetic rats) is different, a fact that might explain the discrepancies between results. However, we may also postulate that the effectiveness of the oligofructose treatment may depend on its satiating effect, and on its effect on incretins production, which has not been reported in other studies. These could be key parameters to measure in the future.

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P < 0·05 v. CT.
† P < 0·05 v. STZ-CT.
‡ P < 0·05 v. STZ-Res.
proximal colon) with the putative effect on GLP-1 production and expression. But other mechanisms to explain a higher portal GLP-1 after oligofructose treatment cannot be excluded because we have also shown that the activity of serum dipeptidylpeptidase IV – responsible for GLP-1 cleavage and inactivation – is decreased during oligofructose treatment.

Even if GLP-1 appears as a good candidate to explain some physiological effects of inulin-type fructans (satiety, glucose homeostasis), other peptides could also be relevant, such as PYY or ghrelin, which were modulated by the treatment, as shown earlier. Oxyntomodulin could also be involved, since it has recently been proposed as a promising proglucagon-derived gut peptide in the control of food intake (Druce et al. 2004). Based on these results, it appears justified to test, in human subjects, the hypothesis that dietary inulin-type fructans could play a role in the management of obesity and diabetes. Other non-digestible/fermentable carbohydrates are prone to ameliorate postprandial glycaemia and insulin sensitivity in healthy human subjects (Robertson et al. 2003). Fermentation has been proposed to be involved in such a protective effect of resistant starch, and in view of our results, it would be interesting to assess the involvement of GLP-1 as a putative mediator of resistant starch also. One study has already reported that treatment of human volunteers with about 20 g oligofructose/d for 7 d was able to increase serum GLP-1 (Piche et al. 2003). Further analysis of the effect of dietary intake of inulin-type fructans (mainly oligofructose-containing products) on incretins production, appetite regulation and glucose metabolism in man are thus expected to bring interesting results.

**Fig. 2.** Effects of oligofructose on gastrointestinal peptides. OFS, oligofructose; GLP-1, glucagon-like peptide-1; DPP IV, dipeptidylpeptidase IV.

**References**


