Augmented GLP-1 Secretion as Seen After Gastric Bypass May Be Obtained by Delaying Carbohydrate Digestion

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Published in: Journal of Clinical Endocrinology and Metabolism

DOI: 10.1210/jc.2018-02661
Publication date: 2019

Document license: Unspecified

Citation for published version (APA):
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The Journal of Clinical Endocrinology & Metabolism
Endocrine Society

Submitted: December 11, 2018
Accepted: March 01, 2019
First Online: March 07, 2019

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Gut hormone secretion in response to carbohydrates

Augmented GLP-1 secretion as seen after gastric bypass may be obtained by delaying carbohydrate digestion

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Received 11 December 2018. Accepted 01 March 2019.
ClinicalTrials.gov registration number: NCT02879955

Context: Exaggerated postprandial Glucagon-like Peptide-1 (GLP-1) secretion seems important for weight loss and diabetes remission after Roux-en-Y gastric bypass (RYGB) and may result from carbohydrate absorption in the distal small intestine.

Objective: To investigate distal (GLP-1; Peptide YY, PYY) and proximal (Glucose-dependent Insulinotropic Polypeptide, GIP) gut hormone secretion in response to carbohydrates hydrolyzed at different rates. We hypothesized that slow digestion restricts proximal absorption, facilitating distal delivery of carbohydrates and thereby enhanced GLP-1 secretion in unoperated individuals, while this may not apply after RYGB.

Design: Single-blinded, randomized, crossover study.

Setting: Hvidovre Hospital, Denmark.

Participants: 10 RYGB- and 10 unoperated matched subjects.

Interventions: 4 separate days with ingestion of different carbohydrate loads, either rapidly/proximally digested (glucose+fructose; sucrose) or slowly/distally digested (isomaltulose; sucrose+acarbose).

Main outcome measures: GLP-1 secretion (area-under-the-curve above baseline). Secondary outcomes included PYY and GIP.

Results: Isomaltulose enhanced secretion of GLP-1 nearly 3-fold (p=0.02) and PYY 9-fold (p=0.08) compared with sucrose in unoperated subjects but had modest effect after RYGB. Acarbose failed to increase sucrose induced GLP-1 secretion in unoperated subjects and diminished the responses by 50% after RYGB (p=0.03). In both groups, GIP secretion was reduced by isomaltulose and even more so by sucrose+acarbose when compared to sucrose intake.

Conclusions: GLP-1 secretion depends on the rate of carbohydrate digestion, but in a different manner after RYGB. Enhanced GLP-1 secretion is central after RYGB, but it may also be obtained in unoperated individuals by delaying hydrolysis of carbohydrates, pushing their digestion and absorption distally in the small intestine.
GLP-1 responses to dietary carbohydrates were exaggerated after gastric bypass. Prolonged digestion led to greatly enhanced GLP-1 secretion in unoperated subjects, but less so after gastric bypass.

Introduction

Roux-en-Y gastric bypass (RYGB) surgery leads to substantial weight loss in morbidly obese patients and has profound effects on type 2 diabetes, resulting in improvements in glycemic control that are superior to those of conventional medical treatments (1,2). Exaggerated postprandial release of the L-cell hormones glucagon-like peptide-1 (GLP-1) and peptide YY (PYY) appears to contribute importantly to improved glucose metabolism (GLP-1) and appetite control (GLP-1 + PYY) postoperatively (3–7). The exact mechanisms behind the exaggerated gut hormone release are incompletely understood, but dietary carbohydrates, as compared to fat and protein, seem to be particularly powerful in stimulating L-cell secretion after the surgery (8,9). The enhanced GLP-1 secretion after RYGB is thought to arise from the delivery of ingested carbohydrates to the distal intestine (10,11), where L-cell density is high (12–14). In addition, the accelerated glucose absorption after the surgery may play a major role since enteroendocrine cells appear to respond to the glucose absorption rate rather than to the presence of glucose in the intestinal lumen (15–18). Accordingly, reestablishing a normal rate of nutrient entry to the intestine after RYGB either by slowly infusing glucose through a tube inserted in the so-called alimentary limb or by administering the food into the bypassed gastric remnant, completely abolishes the postoperative increase in GLP-1 and insulin secretion (11,19,20). The importance of the intestinal site of nutrient delivery is further supported by studies in humans and rodents with diabetes, where an increased postprandial GLP-1 release accompanied by improved glucose tolerance is seen after surgical transposition of an ileum segment to the proximal intestine (21–24). Based on these findings, individuals with intact gastrointestinal anatomy could theoretically achieve significantly enhanced L-cell secretion by delivery of nutrients to the distal small intestine, an approach that might be exploited for the treatment of both diabetes and obesity.

Most dietary carbohydrates need to be digested to monosaccharides before absorption. The disaccharides sucrose and isomaltulose are hydrolyzed to the monosaccharides glucose and fructose by alpha-glucosidase enzymes in the brush border of the small intestine. While the alpha-1,2 glycosidic bond in sucrose is rapidly hydrolyzed, the alpha-1,6 linkage in isomaltulose is more resistant towards enzymatic breakdown (25). Consequently, isomaltulose is digested at a lower rate than sucrose resulting in a prolonged and presumably more distal absorption, which may affect GLP-1 secretion (26–28). The enzymatic activity of alpha-glucosidas can be inhibited pharmacologically by administration of acarbose. Acarbose ingested with sucrose has been found to increase GLP-1 release in unoperated individuals (29–31), while there is little effect when the drug is administered with a mixed meal (32–36), perhaps because the effect is overshadowed by the stimulatory effects of the other nutrients. Taken together, when digestion of carbohydrates is delayed, proximal absorption is assumed to be inhibited, leading to a more distal digestion and absorption and thereby greater release of GLP-1.

The primary objective of the present study was to investigate GLP-1 responses to oral loads of glucose and fructose, ingested either as separate monosaccharides or in the form of the disaccharides sucrose or isomaltulose in RYGB patients and unoperated individuals; and additionally, to investigate the effect of alpha-glucosidase inhibition by acarbose upon sucrose ingestion. We hypothesized that delayed digestion after isomaltulose as well as sucrose + acarbose would lead to distal absorption and thereby enhanced GLP-1 secretion in unoperated individuals, while a similar effect may not be seen after RYGB, where all carbohydrate loads are delivered to the distal intestine due to the surgical rearrangement.
Materials and methods

Participants and ethics
RYGB participants were eligible if they had uncomplicated laparoscopic RYGB surgery >1 year before the study. Exclusion criteria were current HbA1c>48 mmol/mol (>6.5 %) or a history of diabetes, hemoglobin <6.5 mmol/l, pregnancy or breast feeding, and co-morbidities or medications affecting glucose homeostasis or gastrointestinal function. Unoperated control subjects (CON) were matched for sex, age and BMI and fulfilled the same exclusion criteria with the addition of prior complicated surgery to the upper abdomen. Written informed consent was obtained from all participants before inclusion. Prior to initiation of the study, approval was obtained from the Regional Ethics Committee of the Capital Region of Denmark and from the Danish Data Protection Agency and registration was performed at ClinicalTrials.gov (NCT02879955). The study was conducted in accordance with the Helsinki declaration.

Study design
Participants were investigated on 4 experimental days separated by at least 2 days using different oral loads of mono- or disaccharides (provided by BENEO GmbH, Mannheim, Germany) dissolved in 200 mL water: a. 25 g glucose + 25 g fructose, b. 47.5 g sucrose, c. 47.5 g isomaltulose and d. 47.5 g sucrose combined with 100 mg acarbose (net contents, not including the content of water and impurities in the powders). Each of these loads provides ~0.14 mol glucose and fructose. One g of crushed paracetamol (Pamol; Nycomed, Roskilde, Denmark) was added to the solutions to allow assessment of paracetamol absorption as a measure of intestinal entry of the saccharide loads (gastric/pouch emptying). Study days were performed in a randomized order except the sucrose + acarbose day, which was performed last to avoid any carry-over effect of alpha-glucosidase inhibition on subsequent study days. The three other study days were randomized; 10 doublets of papers, representing different order of the test days, were drawn from an envelope, ensuring identical combinations of test days in the two groups.

Experimental day
Participants met after an overnight fast of 10-12 hours, were weighed and placed in a hospital bed at a 45 degrees reclined position throughout the test day, allowing no strenuous activity. A catheter was inserted in an antecubital vein for blood sampling. After three fasting samples, participants ingested 25 ml of water, to which was added, on the last day, 100 mg crushed acarbose (Glucobay, Bayer Pharma AG, Germany), and 5 min after, a steady ingestion over 10 min of the carbohydrate load was started. Blood was sampled frequently for 4 h postprandially (at times 5, 10, 15, 20, 30, 45, 60, 90, 120, 150, 180, 240 min). In addition, blood pressure measurements and visual analogue scores for satiety, hunger, nausea and stomach pain were carried out before and after (at times 30, 60, 90, 120, 180, 240 min) the carbohydrate load.

Sample collection and laboratory analyses
Blood was collected into prechilled EDTA tubes containing a DPP-4 inhibitor (valine-pyrrolidide, final concentration of 0.01 mM; a gift from Novo Nordisk, Bagsværd, Denmark) for analysis of GLP-1, GIP, PYY and glucagon; into EDTA tubes (or EDTA-Eppendorf tubes) for analysis of glucose and paracetamol; and into clot activator tubes for C-peptide measurement. Clot activator tubes were left to coagulate for 30 min (serum) and EDTA tubes were placed on ice and centrifuged without delay at 4°C. EDTA-Eppendorf tubes were centrifuged immediately and plasma for analysis of P-glucose was stored at 5°C before analysis at the end of the test day using YSI model 2300 STAT plus (YSI, Yellow Springs, OH). Samples for analysis of GLP-1, GIP, PYY, glucagon and paracetamol were stored at -20°C and serum at -80°C until batch analysis. Concentrations of C-peptide were determined...
by Immulite 2000 analyzer (Siemens Healthcare Diagnostics Inc., Tarrytown, NY, USA), paracetamol by enzyme immunoassay (Roche/Hitachi cobas c system) and total GLP-1, total GIP and glucagon as previously described (37); total hormone concentrations comprise intact hormone + primary DPP-4 metabolite. Determination of total PYY in plasma was carried out by RIA using a monoclonal antibody MAB8500 as described elsewhere (38).

**Calculations and statistical analyses**

Mean fasting concentrations were calculated as the mean of two fasting samples (three for glucose and C-peptide). Area-under-the-curve (AUC) was calculated using the trapezoidal rule and positive incremental AUC (piAUC) as the AUC above fasting concentrations for evaluation of postprandial secretory responses. Missing blood values (<1%) were imputed. HOMA2-IR was calculated based on triple measurement of glucose and C-peptide in fasting using the HOMA2 model (www.dtu.ox.ac.uk/homacalculator) (39). Wilcoxon signed rank test was used for within-group comparisons of the responses to the different sugar loads with sucrose as reference, and Mann-Whitney test was used for between-group comparisons of RYGB vs. CON. The function “wilcox.exact” from the package “exactRankTests” was applied to compute exact p-values using the Shift-Algorithm by Streitberg & Röhmel, which also corrects for ties. Effect size was quantified as the relative/percentage difference between arithmetic means. The GLP-1 response to the different carbohydrates was the primary endpoint, while all other comparisons were explorative secondary endpoints. Differences are evaluated from p-values after Bonferroni adjustment for multiple comparisons. Thus, p-values have been multiplied by 3 for within-group comparisons and by 4 for between-group comparisons of corresponding test days. An adjusted p-value <0.05 was considered significant. Statistical analysis was performed in R version 3.2.0 (www.R-project.org). Data are expressed as mean ± SEM unless otherwise stated.

**Results**

**Characteristics of participants**

Ten RYGB and ten non-surgical participants matched on sex, age and BMI were included. The groups had similar HbA1c, whereas insulin resistance assessed by HOMA2 was significantly lower after RYGB (table 1). RYGB patients were examined at a median of 3.9 (range: 2.2-5.8) years after surgery.

**Fasting concentrations**

Compared with CON, the RYGB group had significantly lower fasting plasma glucose (5.1 vs. 5.5 mmol/l, p<0.01) and serum C-peptide (524 vs. 833 pmol/l, p=0.02) concentration, while fasting plasma concentrations of gut hormones and glucagon did not differ significantly between groups (table 1). Generally, fasting plasma hormone concentrations did not differ substantially between study days (table 2), but differences did however reach significance for sucrose + acarbose compared with sucrose in both the RYGB (GLP-1, GIP, glucagon) and CON group (GIP).

**Postprandial responses**

**Paracetamol absorption and glycemic excursions**

Paracetamol absorption (as measure of gastric/pouch emptying) was very rapid after RYGB with higher peak values of plasma paracetamol occurring markedly earlier than in CON, while no within-group differences between study days were observed (table 2, figure 1). Glycemic excursions in response to the four different test loads generally reflected the expected digestibility of the sugars with the rapidly absorbed saccharides causing greater peak (glucose + fructose > sucrose > isomaltulose > sucrose + acarbose) and lower nadir of glucose concentration than the slowly absorbed saccharides in both groups although not all
comparisons reached significance (table 2, figure 1). RYGB operated participants were characterized by significantly higher peak plasma glucose compared with CON, but only in response to glucose + fructose and sucrose (adjusted p<0.01 for both), whereas peaks were comparable between groups after ingestion of isomaltulose or sucrose + acarbose (table 2, figure 1).

GLP-1 (primary outcome)
Intake of the slowly digested isomaltulose led to prolonged GLP-1 secretion in both groups. Consequently, isomaltulose enhanced GLP-1 secretion compared with the rapidly absorbed saccharides. In the CON group, isomaltulose ingestion resulted in 170% greater piAUC of GLP-1 (adjusted p=0.02 vs. sucrose) and higher peak concentrations (adjusted p=0.01 vs. sucrose) (table 2, figure 2 and 3), whereas the relative effect after RYGB was much smaller and not significant (piAUC +50 %, adjusted p=0.32 vs. sucrose) (table 2, figure 2 and 3). The GLP-1 responses to sucrose (piAUC) were comparable to the responses induced by glucose + fructose in both RYGB (adjusted p=1.00) and CON subjects (adjusted p=1.00) (figure 2 and 3).

The GLP-1 response elicited by sucrose was diminished by acarbose in RYGB patients, leading to a 50% reduction in piAUC (adjusted p=0.03) and seemingly 30% lower peak levels (adjusted p=0.11), whereas these parameters were not affected by acarbose in CON (table 2, figure 2 and 3).

When compared with CON, the RYGB group was characterized by 3-fold greater overall GLP-1 secretion (piAUC) in response to glucose + fructose and sucrose (adjusted p<0.01 vs. CON for both), but not in response to isomaltulose or sucrose + acarbose (figure 2 and 3). Interestingly, the overall GLP-1 responses (piAUC) to isomaltulose in CON (1288 ± 243 min·pmol/l) were rather similar in magnitude to the responses induced by sucrose (1358 ± 182 min·pmol/l) and glucose + fructose (1319 ± 164 min·pmol/l) in RYGB operated patients (figure 3). However, the secretory profiles were markedly different between the RYGB and CON group for all comparisons with RYGB operated patients reaching much higher peak levels of GLP-1 for all comparisons (table 2, figure 2).

PYY, GIP, C-peptide and glucagon
Isomaltulose also appeared superior to sucrose in stimulating secretion of the other L-cell hormone PYY, but despite 9-fold greater piAUC in CON and a 2-fold increase after RYGB, significance was not reached (adjusted p=0.08 and 0.48, respectively) (figure 2 and 3). In contrast to the impact of alpha-glucosidase blockage on GLP-1, sucrose + acarbose increased piAUC of PYY 3-fold compared with sucrose alone but this was insignicant in both RYGB (adjusted p=0.25) and CON subjects (adjusted p=0.70) (figure 2 and 3). Secretion of PYY (piAUC) tended to be greater in RYGB operated individuals in response to the rapidly absorbed carbohydrates, sucrose (adjusted p=0.11 vs. CON) and glucose + fructose (adjusted p=0.12 vs. CON), but not in response to isomaltulose or sucrose + acarbose (adjusted p=1.00 and 0.87, respectively) (figure 2 and 3).

Secretion of GIP was lower after isomaltulose compared with sucrose in both groups with a 50% reduction in piAUC and a 70% reduction in peak concentration after RYGB (adjusted p<0.01 vs. sucrose for both), while isomaltulose in CON decreased the peak concentration (adjusted p<0.01) and piAUC (adjusted p=0.06) of GIP by 30% compared with sucrose (table 2, figure 2 and 3). Intake of sucrose + acarbose resulted in 90% lower piAUC and 50% lower peak of GIP in both groups (adjusted p<0.01 vs. sucrose for all comparisons). Overall GIP secretion (piAUC) was comparable between the RYGB and CON group and the numerical differences in peak concentration were insignificant (glucose + fructose: adjusted p=0.99, sucrose: adjusted p=0.18, isomaltulose: adjusted p=1.00, sucrose + acarbose: adjusted p=0.11) (table 2, figure 2 and 3).
Alpha-glucosidase inhibition reduced piAUC and peak concentration of C-peptide by 40-50% in both groups (adjusted p<0.01 for sucrose + acarbose vs. sucrose in both RYGB and CON), while no between-group differences were observed (Table 2, figure 1).

Glucagon concentration was suppressed by carbohydrate intake and total AUC of the hormone was comparable within and between groups (Table 2, figure 1).

**Discussion**

In this study, we investigated GLP-1 secretion in RYGB operated patients and matched unoperated individuals in response to different oral loads of simple carbohydrates differing in digestibility. We assumed that slowly digested carbohydrates would bypass proximal absorption and reach more distal gut segments and therefore could be used as an experimental model to explore the importance of intestinal site of delivery for gut hormone secretion. The slowly digested disaccharide isomaltulose led to prolonged and greatly enhanced GLP-1 secretion (+170% compared with sucrose) in unoperated individuals, while a relatively modest and statistically insignificant increase (+50% compared with sucrose) was seen after RYGB where all ingested carbohydrates reach more distal parts of the small intestine. RYGB operated patients were characterized by 3-fold enhanced secretion of GLP-1 in response to the rapidly absorbed carbohydrates glucose + fructose and sucrose, while the difference between the RYGB and control group was less pronounced after intake of isomaltulose. Interestingly, the total secretory responses (piAUC) of GLP-1 after isomaltulose ingestion in unoperated individuals were comparable to the responses induced by sucrose or glucose + fructose in RYGB operated subjects, although the secretory profiles were markedly different. Surprisingly, retarding sucrose digestion by alpha-glucosidase inhibition (acarbose) neither enhanced GLP-1 secretion in unoperated subjects nor after RYGB. In fact, acarbose diminished the sucrose induced GLP-1 responses in the RYGB operated participants.

Glucose is known to stimulate GLP-1 secretion strongly while fructose elicits a modest response, particularly in the presence of glucose, in unoperated individuals (40,41). Exaggerated GLP-1 secretion in response to glucose intake is consistently reported after RYGB and has been linked to faster and more distal absorption of glucose after the surgery, as opposed to the situation in individuals with intact gastrointestinal anatomy where ingested glucose is absorbed exclusively in the proximal intestine with a lower density of L-cells. Enhanced GLP-1 responses to isomaltulose compared with sucrose have been reported by a few other studies in unoperated individuals (26–28) but have not previously been investigated after RYGB. The impact of isomaltulose on GLP-1 secretion may be explained by the slow hydrolysis of the alpha 1,6-bond allowing the glucose and fructose moieties to be absorbed in the distal intestine where L-cell density is highest. Accordingly, distal (jejunal/ileal) glucose infusion in humans has been demonstrated to increase GLP-1 secretion (42,43) and reduce food intake (43) when compared to duodenal infusion, although not consistently (44). In terms of this concept, isomaltulose would presumably not be expected to enhance GLP-1 secretion in RYGB operated patients, but this cannot be ruled out based on the present findings, challenging the hypothesis of distal delivery. However, it should be considered that sucrose absorption after RYGB occurs already in the alimentary limb, whereas isomaltulose is more slowly digested leading to a transfer to the distal small intestine with higher L-cell density, also in these patients. A rodent study comparing isomaltulose and sucrose demonstrated superiority of isomaltulose in stimulating GLP-1 secretion after oral ingestion, equality between the disaccharides after jejunal administration and greater responses to sucrose following ileal administration (45). Thus, it appears that the relationship between carbohydrate digestion rate and GLP-1 secretion depend on the site of delivery to the intestine. However, one must account for the possibility that the results of RYGB may not simply be derived from nutrient rerouting since gut hypertrophia and proliferation as well as
altered L-cell distribution and gene expression could also be involved (46,47). It is quite well established that GLP-1 secretion is closely linked to the rate of glucose absorption (15,18,48). However, the augmented GLP-1 secretion in response to isomaltulose is clearly not a result of accelerated glucose absorption since the glucose absorption rate was attenuated after isomaltulose ingestion (28). Nor is it likely that isomaltulose interacts directly with L-cells since the disaccharide has negligible impact on GLP-1 secretion in vitro (45).

Judging from the glycemic profiles, alpha-glucosidase inhibition by acarbose effectively suppressed sucrose digestion, but somewhat surprisingly, this did not lead to greater GLP-1 secretion in control subjects, again raising doubt about the idea that delaying glucose absorption to distal sites will enhance GLP-1 secretion. Previous studies in unoperated individuals have observed only slightly increased GLP-1 release when acarbose is ingested with sucrose (29,30), and generally no change when the drug is combined with a mixed meal (32–36). Given that absorption of glucose is necessary for GLP-1 secretion also in the ileum (18), the simplest explanation for the lack of effect is that the alpha glucosidase activity was inhibited so much that hydrolysis was partially prevented, leading to malabsorption and transfer of some of the sucrose load to the colon. This would be consistent with the rather flat glucose and C-peptide profiles. The effects of alpha-glucosidase inhibitors are probably influenced by several factors such as the timing of drug administration as well as the dosage and type of agent. Also, prolonged dosage once daily for a week appears to augment sucrose induced GLP-1 secretion to a much greater extent than single-dose administration in unoperated subjects (29). Acarbose has been used in the treatment of reactive hypoglycemia and the drug has previously been demonstrated to blunt postprandial GLP-1 and insulin hypersecretion in eight RYGB operated patients suffering from this condition (49). The same effect has also been observed in a case report of a patient suffering from reactive hypoglycemia after oesophagectomy (50). Thus, the inhibiting effect of acarbose on GLP-1 secretion after RYGB (and not in control subjects) may support that the rapid glucose absorption in the distal intestine is important for the enhanced GLP-1 secretion after the surgery as elegantly demonstrated previously by slowing intestinal glucose delivery in RYGB operated patients (11).

L-cells co-secrete GLP-1 and PYY in exaggerated amounts after RYGB, and there is evidence that these hormones act in synergy to reduce food intake after the surgery (7). PYY responses tended to be increased by isomaltulose compared with sucrose, and again the most robust effect was observed in unoperated individuals. In RYGB operated patients, the inhibition of GLP-1 secretion by acarbose was in sharp contrast to the effect of this drug on PYY, where secretion was clearly not inhibited. It has recently been established that the expression-pattern of L-cells varies considerably along the GI-tract with PYY expressed almost exclusively in the ileum and colon whereas GLP-1 also originates from the proximal intestine (14,18,51–53). In view of this, distal delivery of carbohydrates could augment secretion of PYY more than that of GLP-1. Thus, as discussed above, high dose acarbose administration after RYGB could lead to transfer of undigested sucrose to the colon and generation of short-chain fatty acids (SCFAs), which has been proposed to stimulate L-cell secretion through free fatty acid receptors GPR41 and GPR43 (54–59). The influence of colonic fermentation on gut hormone secretion in humans is incompletely understood, but it appears that SCFA may be particularly effective in stimulating the release of PYY (57,60,61). Thus, colonic transfer and fermentation of undigested sucrose might give rise to a stimulation of PYY release while leaving less sucrose behind in the small intestine to elicit GLP-1 secretion.

Contrary to L-cell secretion, responses of GIP were consistently lower after intake of the slowly digested saccharides in both groups. This agrees with previous findings in unoperated subjects (26–28,30,33) and was expected, considering the higher density of K-cells in the
proximal intestine (14). Overall GIP secretion (i.e., piAUC) was rather similar between the RYGB and control group despite seemingly different secretory profiles. Prospective studies have reported conflicting results regarding the effect of RYGB on postprandial GIP concentrations (62), but the changes are generally modest compared with the changes in L-cell secretion.

Increased meal-related glucagon levels are often reported after RYGB and have been proposed to arise from L-cell stimulation by nutrients in the distal intestine and/or stimulation of pancreatic secretion by fast absorption of amino acids caused by accelerated protein digestion (62,63). In our study, all carbohydrates suppressed glucagon secretion with no substantial differences between RYGB and control subjects, and glucagon was not enhanced by distal digestion, suggesting that other mechanisms besides co-secretion with GLP-1 from L-cells are involved (64). Secretory responses of C-peptide were considerably lowered by acarbose in both RYGB and control subjects in agreement with previous reports (30,32,33,49). Reduced beta-cell stimulation by glucose and incretin hormones following alpha-glucosidase inhibition may explain this finding.

Increased hepatic and peripheral insulin sensitivity are well-established responses to negative energy balance and weight loss and the improvements in these parameters after RYGB therefore come as no surprise (65). However, HOMA2-IR was lower after RYGB than in the matched controls, although our RYGB operated patients were examined in the weight stable phase approximately 4 years after surgery. Thus, the higher insulin sensitivity after the surgery may to some extent be independent of BMI as well as negative energy balance. Improvements in insulin sensitivity after RYGB beyond than what can be predicted from weight loss have been described previously (66).

In conclusion, gastric bypass operated patients are characterized by augmented GLP-1 secretion in response to rapidly absorbed carbohydrates, consistent with fast delivery to and absorption in distal segments of the gut. Accordingly, enhanced secretion of GLP-1 could also be obtained in matched unoperated subjects in response to the slowly and therefore more distally digested disaccharide isomaltulose, which had a modest and statistically insignificant effect in gastric bypass operated patients. By contrast, retarding sucrose digestion using the alpha-glucosidase inhibitor acarbose failed to enhance GLP-1 secretion in unoperated individuals, raising doubt about the importance of distal delivery, while acarbose diminished GLP-1 responses after gastric bypass. Potent inhibition of sucrose hydrolysis and possibly malabsorption caused by the large dose of acarbose employed might explain this. Elucidating the digestive and absorptive processes implicated in gut hormone secretion after gastric bypass may aid the discovery of nutritional or pharmacological modalities mimicking the effects of the surgery.

The Danish Diabetes Academy funded by the Novo Nordisk Foundation, Christoffer Martinussen; H2020 European Research Council http://dx.doi.org/10.13039/100010663, 695069-BYPASSWITHOUTSURGERY, Jens Juul Holst; the Novo Nordisk Foundation, NNF15OC0017188, Carsten Dirksen; the Novo Nordisk Foundation, Sten Madsbad; the Research Foundation for health research of the Capital Region of Denmark, Sten Madsbad; the Internal Research Foundation at Hvidovre Hospital, Christoffer Martinussen

Acknowledgements
We greatly appreciate the technical assistance of Alis Sloth Andersen, Sussi Polmann, Fozia Zia and Jette Nymann (Hvidovre University Hospital, Copenhagen, Denmark) as well as Lene Brus Albæk (Department of Biomedical Sciences, University of Copenhagen, Denmark).
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Disclosure summary:
This work was supported by grants from the Danish Diabetes Academy funded by the Novo Nordisk Foundation; the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement No 695069-BYPASSWITHOUTSURGERY); the Novo Nordisk Foundation (NNF15OC0017188); the Research Foundation for health research of the Capital Region of Denmark and the Internal Research Foundation at Hvidovre Hospital. CM, KNBM, CD, MSV, BH, JJH and SM are affiliated with the Novo Nordisk Foundation Center for Basic Metabolic Research funded by the Novo Nordisk Foundation. VBK has no disclosures.

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Figure 1. Data are mean ± SEM. Concentration of glucose, C-peptide, glucagon and paracetamol in response to intake of glu+fru (dotted black line), suc (solid black line, black circles), iso (solid gray line, gray squares) and suc+aca (dashed black line, white triangles) in Roux en-Y gastric bypass operated patients (RYGB) to the left and control subjects (CON) to the right. glu=glucose, fru=fructose, suc=sucrose, iso=isomaltulose, aca=acarbose.

Figure 2. Data are mean ± SEM. Concentration of Glucagon-like Peptide-1 (GLP-1), Peptide YY (PYY), and Glucose-dependent Insulinotropic Polypeptide (GIP) in response to intake of glu+fru (dotted black line), suc (solid black line, black circles), iso (solid gray line, gray squares) and suc+aca (dashed black line, white triangles) in Roux en-Y gastric bypass operated patients (RYGB) to the left and control subjects (CON) to the right. glu=glucose, fru=fructose, suc=sucrose, iso=isomaltulose, aca=acarbose.

Figure 3. Data are mean ± SEM. Secretory responses of Glucagon-like Peptide-1 (GLP-1), Peptide YY (PYY), and Glucose-dependent Insulinotropic Polypeptide (GIP) assessed as the positive incremental area-under-the-curve with Roux en-Y gastric bypass operated patients (RYGB) to the left and control subjects (CON) to the right. *adjusted p<0.05 **adjusted p<0.01 vs. suc (within-group comparison using Wilcoxon signed rank test followed by Bonferroni adjustment for multiple comparisons). §adjusted p<0.05 §§adjusted p<0.01 vs. RYGB (between-group comparison of corresponding test days using Mann-Whitney test followed by Bonferroni adjustment for multiple comparisons). glu=glucose, fru=fructose, suc=sucrose, iso=isomaltulose, aca=acarbose.

Table 1. Baseline characteristics and fasting concentrations for Roux en-Y gastric bypass (RYGB) and control (CON) participants.

<table>
<thead>
<tr>
<th></th>
<th>RYGB</th>
<th>CON</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Gender (m/f)</td>
<td>5/5</td>
<td>5/5</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>43.3 ± 1.8</td>
<td>42.7 ± 3.2</td>
<td>0.97</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>33.0 ± 1.7</td>
<td>32.5 ± 1.8</td>
<td>0.58</td>
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<tr>
<td>HbA1c (mmol/mol)</td>
<td>36.9 ± 0.9</td>
<td>37 ± 0.8</td>
<td>0.60</td>
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<tr>
<td>HOMA2-IR C-peptide</td>
<td>1.16 ± 0.08</td>
<td>1.89 ± 0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>Fasting glucose (mmol/l)</td>
<td>5.1 ± 0.08</td>
<td>5.5 ± 0.08</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Fasting C-peptide (pmol/l)</td>
<td>524 ± 34</td>
<td>833 ± 103</td>
<td>0.02</td>
</tr>
<tr>
<td>Fasting glucagon (pmol/l)</td>
<td>6.4 ± 1.1</td>
<td>9.0 ± 1.8</td>
<td>0.11</td>
</tr>
<tr>
<td>Fasting GLP-1 (pmol/l)</td>
<td>7.3 ± 1.1</td>
<td>7.7 ± 0.9</td>
<td>0.52</td>
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<tr>
<td>Fasting PYY (pmol/l)</td>
<td>6.0 ± 0.8</td>
<td>5.7 ± 0.5</td>
<td>0.73</td>
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<tr>
<td>Fasting GIP (pmol/l)</td>
<td>6.4 ± 1.2</td>
<td>6.0 ± 1.3</td>
<td>0.67</td>
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</table>

Data are mean ± SEM. For calculation of fasting concentrations in each group, the mean of the four test days for each study participant was used. P-values for between-group comparison using Mann-Whitney test. BMI=Body Mass Index, HOMA2-IR C-peptide=homeostatic model assessment of insulin resistance based on C-peptide, GLP-1=Glucagon-like Peptide-1, PYY=Peptide YY, GIP=Glucose-dependent Insulinotropic Polypeptide.

Table 2. Postprandial responses to ingestion of simple carbohydrates in Roux en-Y gastric bypass (RYGB) and control (CON) participants.

<table>
<thead>
<tr>
<th></th>
<th>RYGB</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
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<td>10</td>
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<tr>
<td>Glucose</td>
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<td></td>
</tr>
<tr>
<td>fasting (mmol/l)</td>
<td>5.0 ± 0.09</td>
<td>5.1 ± 0.11</td>
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<tr>
<td>MAX (mmol/l)</td>
<td>9.8 ± 0.38</td>
<td>9.3 ± 0.37</td>
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<tr>
<td>iso</td>
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<tr>
<td>fasting (mmol/l)</td>
<td>5.1 ± 0.12</td>
<td>6.7 ± 0.23</td>
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<tr>
<td>MAX (mmol/l)</td>
<td>7.4 ± 0.36**</td>
<td>6.7 ± 0.23**</td>
</tr>
<tr>
<td>suc+aca</td>
<td></td>
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<tr>
<td>fasting (mmol/l)</td>
<td>5.0 ± 0.07</td>
<td>5.5 ± 0.09</td>
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<tr>
<td>MAX (mmol/l)</td>
<td>8.1 ± 0.21**</td>
<td>7.7 ± 0.17**</td>
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<tr>
<td>glu+fru</td>
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<tr>
<td>fasting (mmol/l)</td>
<td>5.4 ± 0.11**</td>
<td>5.5 ± 0.09</td>
</tr>
<tr>
<td>MAX (mmol/l)</td>
<td>8.1 ± 0.21**</td>
<td>7.7 ± 0.17**</td>
</tr>
<tr>
<td>suc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fasting (mmol/l)</td>
<td>5.5 ± 0.11</td>
<td>5.6 ± 0.09**</td>
</tr>
<tr>
<td>MAX (mmol/l)</td>
<td>8.1 ± 0.21**</td>
<td>7.7 ± 0.17**</td>
</tr>
<tr>
<td>iso</td>
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<tr>
<td>fasting (mmol/l)</td>
<td>5.5 ± 0.11</td>
<td>5.6 ± 0.09**</td>
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<tr>
<td>MAX (mmol/l)</td>
<td>8.1 ± 0.21**</td>
<td>7.7 ± 0.17**</td>
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<tr>
<td>suc+aca</td>
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<tr>
<td>fasting (mmol/l)</td>
<td>5.5 ± 0.11</td>
<td>5.6 ± 0.09**</td>
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<tr>
<td>MAX (mmol/l)</td>
<td>8.1 ± 0.21**</td>
<td>7.7 ± 0.17**</td>
</tr>
<tr>
<td>Indicator</td>
<td>min (mmol/l)</td>
<td>4.1 ± 0.17</td>
</tr>
<tr>
<td>------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>C-peptide</td>
<td>fasting (pmol/l)</td>
<td>512 ± 25</td>
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<tr>
<td></td>
<td>max (pmol/l)</td>
<td>2888 ± 155</td>
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<td></td>
<td>piAUC (min·nmol/l)</td>
<td>129 ± 8</td>
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<tr>
<td>Glucagon</td>
<td>fasting (pmol/l)</td>
<td>6.5 ± 1.7</td>
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<tr>
<td></td>
<td>min (pmol/l)</td>
<td>2.3 ± 0.5</td>
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<tr>
<td></td>
<td>tAUC (min·pmol/l)</td>
<td>1227 ± 176</td>
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<tr>
<td>Paracetamol</td>
<td>fasting (pmol/l)</td>
<td>5.8 ± 1.4</td>
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<td>max (pmol/l)</td>
<td>49 ± 7.4</td>
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<tr>
<td>PYY</td>
<td>fasting (pmol/l)</td>
<td>6.6 ± 1.1</td>
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<td></td>
<td>max (pmol/l)</td>
<td>14 ± 0.9</td>
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<tr>
<td>GIP</td>
<td>fasting (pmol/l)</td>
<td>7.2 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>max (pmol/l)</td>
<td>50 ± 7.4</td>
</tr>
</tbody>
</table>

Data are mean ± SEM. The mean fasting concentration was also considered when identifying the maximum (max) and minimum (min) value. *adjusted p<0.05 **adjusted p<0.01 vs. suc (within-group comparison using Wilcoxon signed rank test followed by Bonferroni adjustment for multiple comparisons). §adjusted p<0.05 §§adjusted p<0.01 vs. RYGB (between-group comparison of corresponding test days using Mann-Whitney test followed by Bonferroni adjustment for multiple comparisons). glu=glucose, fru=fructose, suc=sucrose, iso=isomaltulose, aca=acarbose, GLP-1=Glucagon-like Peptide-1, PYY=Peptide YY, GIP=Glucose-dependent Insulinotropic Polypeptide, AUC=area-under-the-curve, tAUC=total AUC, piAUC=positive incremental AUC (see figure 3 for piAUC of GLP-1, PYY and GIP).