Effect of three different bariatric obesity surgery procedures on nutrient and energy digestibility using a swine experimental model

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Abstract

Morbid obesity is a worldwide health concern that compromises life quality and health status of obese human subjects. Bariatric surgery for treating morbid obesity remains as one of the best alternatives to promote excess weight loss and to reduce co-morbidities. We have not found studies reporting nutrients and energy balance considering digestibility trials in humans following surgery. The purpose of this study was to determine protein, lipid, fiber, energy, calcium, and phosphorous digestibility in a swine model that underwent ileal transposition (IT), sleeve gastrectomy with ileal transposition (SGIT), Roux-en-Y gastric bypass (RYGBP), and with sham operated animals (SHAM). Thirty-two pigs were randomly assigned to four laparoscopic procedures: IT (n = 8), RYGBP (n = 8), SGIT (n = 8), and Sham-operated pigs (n = 8). From day 0 postsurgery to 130, pigs were weighed monthly to determine live weight and weight gain was calculated for each month postsurgery until day 130. Food intake in a metabolic weight basis was calculated by measuring *ad libitum* food intake at day 130. Swine were fitted into metabolic crates to determine digestibility coefficients of dry matter, protein, fat, fiber, ash, energy, calcium, and phosphorous from day 130. A one-way ANOVA and Student–Newman–Keuls were used to detect differences in weight, food intake, and digestibility coefficients. Digestibility values for dry matter, fiber, phosphorus, and energy showed no differences among groups ($P > 0.05$). However, significant differences ($P \leq 0.05$) were encountered among groups for fat, protein, ash, and calcium digestibilities. The RYGBP procedure, when applied to the pig model, significantly reduced calcium, fat, and ash digestibility, which did not occur with SGIT or IT procedure, when compared with Sham-operated animals.

Keywords: Swine, bariatric surgery, animal model, digestibility

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Introduction

The prevalence of obesity and morbid obesity in adults and children has risen dramatically.¹ The use of surgical techniques is increasing when medical therapy, physical activities, and psychological support fail to reverse the morbid obese condition.^{2,3} Bariatric surgery has been shown to be an effective treatment for patients with severe obesity and/or for patients suffering from type II diabetes mellitus.⁴ In addition to significant weight loss, surgery for morbid obesity is also associated with short- to medium-term improvements in comorbidities and quality of life.⁵ Surgical procedures designed to provoke excess weight loss are generally focused on reducing the volume of part of the digestive tract to decrease food intake and/or inducing malabsorption of nutrients by reducing the functional length of the small intestine and thus, reducing nutrient digestion and absorption.⁶

Gastric bypass (GBP) was first described and performed by Mason and Ito in 1969 and combines restriction and malabsorption components.⁷ Different variations on GBP have been developed, including the Roux-en-Y gastric bypass (RYGBP). The RYGBP surgery involves reducing the size of the stomach to a 15–30 mL pouch (90% gastric exclusion) from the upper stomach as the restrictive component, without removing the remaining stomach. A 150 cm long alimentary limb is created in the small intestine and anastomosed to the gastric pouch, thus intake bypasses the remnant stomach and duodenum, creating the malabsorption element.^{8,9} The RYGBP is considered by many to be one of the most effective procedures to promote weight loss in obese subjects. However, there is evidence that this surgery can lead to nutrient deficiencies, at least in terms of protein, calcium, vitamin D, and iron.^{10,11}

A less invasive restrictive technique as compared to RYGPB is the sleeve gastrectomy (SG). This surgical technique, which involves the removal of approximately 75% of the stomach, has become increasingly popular due to its safety¹² and relative simplicity. Furthermore, it has been shown to result in similar weight losses as those in patients following to GBP.¹³

An alternative method, ileal transposition (IT), described by Koopmans et al. (1982), consists in the removal of a small segment of the terminal ileum and its incorporation into the duodenum, via three transections within the small intestine. This surgery, rather than involving restriction and malabsorption components, was designed so that ingested nutrients would have an earlier contact with ileal cells, to induce the release of hormones such as glucagon-like peptide-1 and peptide tyrosine-tyrosine (PYY 3–36), two peptides that promote satiety.^{14,15} The SG surgical technique can be combined with IT.

In human patients it is difficult to carry out valid comparisons of the effectiveness (degree of weight loss) of these different surgical procedures. Moreover, whereas to some degree malabsorption can be monitored by routine blood sampling,^{16,17} the effect of the different surgical procedures on the digestibility of nutrients cannot be easily and precisely determined. It is important to know which nutrients have low digestibilities in patients following the surgical procedures, since in the long term, a low nutrient digestibility could provoke nutritional problems. If certain nutrients are shown to have a low digestibility in patients following the different surgical procedures, action measures can be taken with the patients to avoid nutritional deficiencies.

Whereas determinations on the effectiveness of different procedures and longer term effects on nutrient digestibilities are difficult to determine in humans, animal models can be used for experimental procedures. Pigs are considered similar to humans in many aspects such as anatomy, morphology, and physiology. Thus, they have been widely used as models for biomedical research in disciplines such as cardiology,¹⁸ immunology,¹⁹ infection diseases,²⁰ genomics,²¹ wound healing,²² and renal complications.²³ Based on similarities in terms of gastrointestinal morphology, omnivorous habits, and metabolism, swine are also considered to be adequate models for human nutrition,²⁴ to study food intake and obesity,²⁵ and to test for and treat diabetes.²⁶

Thus, from a practical point of view, the pig is a suitable model animal to conduct digestion and balance studies, due to the ease of accurately measuring feed and/or nutrient intake as well as measuring fecal output of the non-digested nutrients in this animal.

Therefore, the objective of this study was to evaluate weight gain in growing pigs and determine crude protein, total fat, acid detergent fiber, energy, calcium, and phosphorous apparent total tract digestibility in following RYGPB, IT, sleeve gastrectomy with ileal transposition (SGIT) when compared with SHAM operated animals.

Materials and methods

All animals underwent pre- and postoperative care according to a previously approved animal welfare protocol and procedures by the Institutional Animal Care and Use Committee of Pontificia Universidad Católica de Chile (Santiago, Chile). The experiment was conducted according to internationally accepted principles and guidelines for the care and use of laboratory animals.²⁷

Pigs

Thirty-two crossbred (Large white × Landrace) male pigs, 22.4 ± 1.8 kg (70 ± 5 days of age) were purchased from a commercial farm and housed in the animal facilities of the Department of Animal Sciences, Pontificia Universidad Católica de Chile (Santiago, Chile) for one week prior to surgery to allow them to accustom to the facilities and management. Animals were fed *ad libitum* with a commercial diet for growing pigs (Concentrados Cisternas®, Santiago, Chile) formulated to meet or exceed nutrient and energy requirements.²⁸ Animals were initially housed in four collective pens (eight pigs per pen) within the same ventilated barn with controlled temperature of $20 \pm 2^\circ\text{C}$. During the first week, the animals were weighed (Iconix FX-1, Precisión Hispana, Santiago, Chile), identified with an ear tag, dewormed (1% Ivermectin, 1 mL/35 kg sc, Crack® Laboratorio Chile, Chile), injected with vitamins (Vitamin ADE, 0.5 mL/animal im, Drag Pharma Invetec, Chile), and vaccinated against erysipelas (2 mL/animal sc, Química Holanda, Chile) and mycoplasma (2 mL/animal sc, Intervet Veterinaria, Chile).

Experimental design and treatments

The pigs were randomly assigned to one of four experimental groups with eight pigs per group. The animals in each group received a different bariatric laparoscopic procedure or SHAM. The surgical procedures were conducted two weeks after the animals arrived. Eight pigs underwent IT, eight were submitted to the SGIT, eight were assigned to the RYGPB with a 300 cm alimentary limb, and eight pigs constituted the Sham-operated group (SHAM).

Surgical technique

Surgery was conducted by gastrointestinal surgeons with experience in advanced laparoscopy and bariatric surgery. The SGIT, IT, RYGPB, and SHAM operations were performed in pigs as described by Boza et al.²⁹ The SHAM operation consisted of making three incisions along the small intestine without removing or affecting either the anatomy or functionality of any component of this organ.

Animal feeding and handling conditions

The feeding protocol before and after surgery is described below. Twenty-four hours prior to the surgery, animals were housed individually and a liquid diet was provided for 24 h to prevent vomiting or severe gastrointestinal distention caused by feed residues. From 12 h before beginning each

surgical procedure, animals were maintained strictly free of water or any other liquids. Following the surgical procedure, animals were maintained without food and water by mouth for the first 12 h and then gradually advanced from water to 1–2 L of semi-skimmed liquid milk (prepared at the concentration recommended on the packaging). In some cases, and to increase the energy content of the milk, maltodextrine (10 g/L) was added. The animals were given access to the liquid diet in feeders while being continuously observed for signs such as vomiting, pain, or lack of appetite over the first postoperative month. Following this month, the diet was gradually changed, over a period of one week, to a solid diet that the animals received for the remainder of the study.

Once the animals had recovered from the anesthetic (12 ± 2 h after surgery) they were housed for 24 h in individual pens (2.0 m $\times$ 2.0 m) with a concrete-type floor, nipple-type waterers, and wide feeders. The environmental temperature was maintained between 22 and 26°C, using heaters and infrared lamps as required.

For five months following the surgical procedures, pigs were housed in collective pens. However, during one week every month postsurgery, pigs were housed individually to record *ad libitum* feed intake. A seven-day register was used to calculate the average daily feed intake per month. At the end of this five-month period of surgery recovery, animals were 220 ± 5 days old. Live weight of each pig was recorded weekly at 8:00 am following 12 h of fasting.

Digestibility trials to determine nutrient and energy absorption

Five months following the surgical procedures (the animals were 220 days old), an *in vivo* apparent total tract digestibility trial was carried out following the method described by Schneider and Flatt in 1975.³⁰ Pigs were housed individually in metabolic crates specially designed to allow a complete collection of feces and urine separately.

All pigs were fed with the same ground diet, a balanced commercial meal for growing pigs formulated to meet or exceed nutritional requirements established by Nutritional Research Council (1998).²⁸ As a carbohydrate source the diet included corn, oats, and wheat middlings. Fat was provided in the diet as vegetable oil. Soybean meal was utilized as a source of protein and crystalline amino acids (L-lysine, DL-methionine, and L-theonine) were added in small quantities. A commercial premix was added to fulfill all vitamin and mineral requirements. The chemical composition of the diet is given in Table 1.

The digestibility experiment within the metabolic crate was carried out over a period of 12 days. The first four days consisted of an adaptation period to the metabolic crates and daily routine. The following eight days (days 5–12) were split into two four-day periods. From days 5–8 animals were fed *ad libitum* to calculate intake. From day 8, the animals were restricted to 85% of their *ad libitum* intake with a complete fecal collection being made on days 9–12. We used 1 g of ferric oxide in 100 g of feed to mark with color feces to ensure we were collecting at 85% of *ad libitum*

Table 1 Chemical composition of the experimental diet (dry matter basis)

Item	Experimental diet
Dry matter (g/100 g)	88.9
Ash (g/100 g)	8.2
Crude fiber (g/100 g)	7.1
Crude fat (g/100 g)	6.6
Crude protein (g/100 g)	14.2
Acid detergent fiber (g/100 g)	8.6
Neutral detergent fiber (g/100 g)	28.4
Calcium (g/100 g)	1.35
Phosphorous (g/100 g)	0.24
Gross energy (kcal/kg)	4399.1
Metabolizable energy (kcal/kg)*	3226.0

*Calculated (NRC²⁸).

intake, thus avoiding confounding the collection from the *ad libitum* period. Feces were collected hourly, weighed, refrigerated, and labeled. Of the total feces collected daily, a sample of 10% of the total amount was frozen at -20°C . Following this period samples were thawed, pooled, and mixed. A subsample of 500 g of feces from each pig was analyzed.

Chemical analyses of feed and feces

Dry matter was determined according to AOAC (2000) methods.³¹ Ash content (representing the mineral fraction of foods) was quantified by burning samples at 550°C for 12 h in a muffle furnace. Total fat was measured using the method described by Sukhija and Palmquist³²; crude protein ($\text{N} \times 6.25$) was measured using the Kjeldahl method in a Kjell-Foss 16200 autoanalyzer; acid detergent fiber was determined using the Van Soest method.³³ Gross energy was determined with an IKA-C 400 bomb calorimeter (IKA Werke, Janke & Kunkel, Staufen, Germany). Calcium was analyzed by flame atomic spectrophotometry (SpectrAA 220 FS, Varian, Springvale, Australia) and phosphorous was assayed using the vanadate colorimetric method described by Biomérieux (Biomérieux 61571, Charbonnières-les-bains, France).

Digestibility coefficients calculations

After samples were analyzed, protein, lipid, fiber, energy, calcium, and phosphorous digestibility coefficients were determined by calculating the percentage of nutrient that appeared in the feces as:

$$\text{Nutrient digestibility coefficient (ND),} \\ \% = [(\text{NI} - \text{NO})/\text{NI}] \times 100$$

where NI = nutrient quantity in oral intake and NO = nutrient output in feces (dry matter basis).

Statistical analysis

The data were tested for normality using the Shapiro–Wilk test. Data that were not normal were transformed or log transformed as appropriate. Data for live weight at day 0, 60, and 130; weight gain between days 0 and 60, and 60 and 130, as well as the overall period; and digestibility coefficients were analyzed using the one-way ANOVA procedure to determine whether statistical differences were present between treatments (surgical procedures). A level of $P < 0.05$ was considered significant. When P -value was less than or equal to 0.05 a Student–Newman–Keuls test for multiple comparisons was conducted. All statistical analyses were conducted using the statistical analyses software (SAS/STAT Version 6.10; SAS Institute, Cary, NC).

Results

Live weight and weight gain

Preoperative weight and for the first, second, and third postoperative months were reported and analyzed in Boza et al.²⁹ Nevertheless, extra data for weight are reported in Table 1. At day 130 postsurgery and prior to start the digestibility trial, SHAM pigs had the greatest live weight, followed by the IT animals, with the SGIT and RYGBP animals having the lowest live weights ($P < 0.0001$). The weight gain values for the overall period (day 0–130) followed the same pattern, although differences in weight gain between SHAM and IT animals were not observed for the first 60 days during which the SGIT and RYGBP animals had significantly lower live weight and weight gain ($P < 0.0001$).

Digestibility

Digestibility values for dry matter, fiber, phosphorus, and energy (Table 3) showed no significant differences among groups ($P > 0.05$). In contrast, fat, protein, ash, and calcium digestibility values showed significant differences among groups ($P \leq 0.05$). Total fat and protein digestibility in RYGBP pigs was lower than that for IT, SGIT, and SHAM animals ($P \leq 0.05$). Ash digestibility was greatest in SHAM and statistically lower in RYGBP pigs ($P \leq 0.05$). However, no differences were found among SHAM, IT, and SGIT and among IT, SGIT, and RYGBP animals. Values for calcium digestibility followed the same pattern as those for ash digestibility.

Discussion

The four experimental surgical procedures: RYGBP, IT, SGIT, and SHAM were designed to either reduce the volume of part of the digestive tract and/or induce malabsorption of nutrients. Both RYGBP and SGIT were designed to limit food intake by creating a small gastric pouch and a gastric tube, respectively. The RYGBP procedure has a malabsorptive component as well, with a reduced nutrient absorption due to the bypass of the long limb of the small intestine.³⁴ Thus, nutrients reaching the small intestine have less contact with bile salts and the pancreatic/intestinal enzymes necessary for digestion and subsequent absorption of the nutrients. On the other hand, Ileal transposition

surgery (IT group) as evaluated in this experiment was designed to promote satiety due to the release of hormones that modulate eating behavior.³⁵ The SGIT procedure has a combination of volume restriction and the eating-behavior switch component.²⁹ In this study, eight pigs were also submitted to a SHAM operation, to ensure that differences observed were not due solely to going through a surgical procedure.

As described by Boza et al.²⁹ all animals involved in this experiment lost weight during the first month postsurgery, probably due to a combination of the nutritional plan, which was restricted and designed to avoid vomiting, dumping syndrome, dehydration, flatulence, and other adverse complications along with the effects of recovering from the different surgeries.³⁶ By the end of day 60 postsurgery, the SHAM animals had a significantly greater weight gain than all of the other animals (Table 2). This difference was even more noticeable during the period 60–130 days postsurgery, when the animals should have recovered completely from the surgical procedures. The period 60–130 days gives an indication of the real effect of the different treatments applied. The growth rates of the animals subjected to the IT surgery were 67% that of the SHAM animals. While the growth rates of the animals subjected to the SGIT and RYGBP procedures were only 22 and 16%, respectively, that of the SHAM animals during this period, with no significant difference between the animals that were subjected to the SGIT and RYGBP procedures. If this information was extrapolated to that which could be expected from human adult patients, a more rapid weight loss could be expected from patients subjected to the SGIT and RYGBP procedures than those solely subjected to the IT procedure. However, in this study, the IT procedure by itself did significantly affect the weight gain of the animals.

In Table 3, the food intakes of each group of animals 130 days following surgery are reported. Given that there were significant differences in the bodyweight of the animals at the different experimental groups, the feed intakes are also reported on a metabolic body weight basis, which allows for a more valid comparison between the groups. It is interesting to note that there was no significant difference in the feed intake of the pigs in the SHAM group compared with those in the IT group at this point in time. The IT surgery procedure was designed to decrease eating behavior,¹⁴ but as reported in Boza,²⁹ in this study pigs submitted to the IT surgery had slightly (but significantly) lowered food intakes at the third month postsurgery than the SHAM animals but by the fifth month there was no difference. The animals in the SGIT group also did not have a significantly lower feed intake on a metabolic body weight basis by day 130, which was surprising, given that this surgical procedure includes a restrictive component with sectioning of the stomach. Some studies have shown that patients who failed to lose excess weight or regain weight after SG and RYGBP may need a revisional surgery to correct stomach or pouch dilatation after a long-term follow-up.^{35,37} In contrast, the animals in the RYGBP groups had a significantly lower feed intake than all of the other animals, which would have been due to the restrictive component of this surgery.

Table 2 Pig live weight and weight gain evolution for the first 130 days following surgery and feed intake 130 days following surgery

	IT	SGIT	RYGBP	SHAM	SEM	P [†]
Live weight (kg)						
Day 0 (preoperative)	23.6	27.5	25.2	20.2	2.3	0.1324
Day 60 following surgery	36.0 ^a	28.3 ^b	26.5 ^b	39.7 ^a	2.8	0.0002
Day 130 following surgery	57.2 ^b	35.4 ^c	31.5 ^c	71.2 ^a	6.9	<0.0001
Weight gain (kg)						
Days 0–60	12.4 ^b	0.8 ^c	1.3 ^c	19.5 ^a	0.1	<0.0001
Days 60–130	21.2 ^b	7.1 ^c	5.0 ^c	31.5 ^a	0.1	<0.0001
Overall (days 0–130)	33.5 ^b	7.7 ^c	6.3 ^c	51.0 ^a	0.1	<0.0001
Food intake at day 130 (kg/day)	2.4 ^a	1.5 ^b	1.0 ^c	2.79 ^a	0.3	<0.0001
Food intake at day 130 on a metabolic body weight basis [‡] (g/kg ^{0.75})	117.2 ^a	101.8 ^a	72.5 ^b	114.6 ^a	10.0	0.0034

*x + SEM; n=8 in each group. Data were transformed or log transformed if appropriate before analysis.

[†]Numbers in a row with the same superscript did not significantly differ (p < 0.05).

[‡]Intake kg per kg bodyweight^{0.75}.

IT: ileal transposition; RYGBP: Roux-en-Y gastric bypass; SGIT: sleeve gastrectomy with ileal transposition; SHAM: SHAM operation.

Table 3 Fecal apparent digestibility *in vivo* (mean ± SEM) in pigs who underwent different bariatric surgeries. All digestibility values are measured as percentages*

	IT	SGIT	RYGBP	SHAM	SEM	P-value
Dry matter	73.5	74.9	69.8	73.0	1.7	0.2248
Ash	33.9 ^a	26.9 ^{ab}	19.9 ^b	43.0 ^a	5.9	0.0282
Total fat	60.8 ^a	67.8 ^a	51.0 ^b	63.8 ^a	3.7	0.0068
Crude protein	77.6 ^a	77.2 ^a	70.6 ^b	76.7 ^a	1.8	0.0187
Fiber	23.1	23.8	15.0	20.6	4.2	0.5085
Calcium	27.4 ^{ab}	25.5 ^{ab}	10.4 ^b	41.1 ^a	6.8	0.0106
Phosphorous	37.2	43.0	35.1	44.7	3.7	0.2071
Energy	73.7	75.4	69.6	72.8	1.7	0.1312

*Numbers in a row with the same superscript did not significantly differ (p < 0.05).

IT: ileal transposition; RYGBP: Roux-en-Y gastric bypass; SGIT: sleeve gastrectomy with ileal transposition; SHAM: SHAM operation.

There can be both feed and animal effects on the total tract digestibility coefficients of nutrients and energy in pigs. Firstly, these coefficients can be affected by the diet chemical composition and feed processing and secondly, animal factors such as body weight, genotype, sex, and physiological stage will also exert effects.³⁸ In the present study, we only used growing castrated males of the same age from the same genetic line, which had access to the same diet (feed composition and processing); so the only factor of variation between groups was the surgical procedure.

The *in vivo* apparent digestibility coefficient results showed no differences for dry matter, fiber, phosphorous, and energy among the four experimental treatments (Table 3). There were, however, differences among treatments for protein, fat, ash, and calcium digestibility. For protein and fat digestibility coefficients, there were no differences between SGIT, IT, and SHAM procedures, but all were significantly greater than RYGBP pigs. This could explain the cases of protein deficiency in human patients that have undergone RYGBP surgery, that have shown decreased serum albumin concentrations.³⁶ The reduced protein digestibility values should be taken into

consideration when designing diets for human patients following RYGBP surgery, to ensure that protein deficiencies do not occur.

Lipid digestibility depends on several factors. Firstly, fat digestibility can vary among fat and oil sources due to the different fatty acid length, degree of unsaturation, and processing. However, in this study the same fat source was used for all treatments. Considering the physiological process of digestion and absorption of dietary fats, biliary salt production and release to the intestinal lumen in the presence of lipids is dependent on the age and physiological stage of the animal. Thus, 21- to 28-day-old pigs do not produce sufficient amounts of biliary salts to fully emulsify dietary lipids, whereas the pigs used in the present study would have had the capability to digest fats and oils up to an inclusion level of 6%.³⁸ In the present study vegetable oil was used as the fat source. This fat source has been reported to have a medium to high digestibility in swine²⁸ at 6.6% of the diet as-fed basis in the growing pig. However, in RYGBP operated animals, the digesta bypasses the bile duct so a decreased value for fat digestibility is to be expected.

The digestibility results suggest that SGIT and IT did not significantly alter the digestion and absorption of the

evaluated nutrients or energy, which makes sense considering that these methods do not involve a malabsorption component.

No studies that report digestibility values in humans following bariatric surgery were found in the literature. Gandarillas et al. reported values from *in vivo* apparent digestibility trials for three different lengths of limbs in RYGBP in the pig model, showing a significant reduction in ash digestibility regardless of the limb length used. Calcium and phosphorous digestibility coefficients were decreased as alimentary limb length was increased ($P < 0.05$).³⁹ In the present study, protein digestibility was lower ($P < 0.05$) in RYGPB as compared with SGIT, IT, and SHAM animals in contrast to the lack of differences reported by Gandarillas et al.³⁹

As mentioned earlier, restrictive and/or malabsorptive bariatric surgery has a potential to cause nutritional and metabolic complications, mostly due to the extensive surgically induced anatomical changes in the patient's gastrointestinal tract. Particularly in RYGBP patients, the most common micronutrient deficiencies reported are for vitamin B12, calcium, iron, and Vitamin D.¹⁰ Moreover, this surgery interferes with folate, copper, and zinc absorption.⁴⁰ Vitamin D and calcium are well-known deficiencies and the results from the present study are consistent with this; calcium directly, and vitamin D, which is a fat-soluble vitamin, given that the digestibility of fat was also lower in the pigs following the RYGBP surgery. It is important to note that vitamin D is required for the synthesis of calcium binding protein that is necessary and the main regulator for calcium absorption.⁴¹ In human studies, Chapin et al. reported severe bone loss in patients that underwent RYGBP, which would be consistent with these results.⁴² These deficiencies are likely to be due to the absorption sites of these nutrients, in the duodenum and jejunum⁴³ sites that are bypassed in a great proportion with RYGBP. Moreover, as calcium in food is present in complexes that require gastric acid secretions (enzymes and low pH) to break it down to an absorbable form, patients who undergo RYGBP are likely to be even more at risk of low calcium absorption, which may increase their risk of osteoporosis. In light of these findings, it can be recommended that humans who undergo RYGBP surgery may require additional calcium and vitamin D supplements. Alexandrou et al. compared nutritional deficiencies in human patients in the four years following RYGBP and SG surgeries and found vitamin D, vitamin B12, and folate deficiency in patients who underwent both surgeries.⁴⁴

Despite the effect of malabsorption of nutrients and energy found in RYGBP, nutrients that are not digested by small intestine and pancreatic enzymes pass through the hindgut (cecum and large intestine) serving as substrate for microbial growth, and gas production leading to flatulence and other undesirable effects.

Conversely, SGIT surgery combines the restrictive effect to decrease food intake (but less severe than RYGBP) of SG; with an IT, a non-malabsorption technique that is focused on the target action of hormones and peptides that encourage an early satiety, thus further reducing food intake. SG is purely restrictive by itself, inducing digestive symptoms

and food intolerance due to pre- and postsurgical eating disorders. In SG, iron deficiency has been reported, especially in menstruating women.⁴⁵

Finally, the pig represents a good model for testing nutrient absorption after bariatric surgery and may help to explain results of blood analyses follow-up programs or bone health metabolism studies as surgeon often perform in human patients. The RYGBP procedure reduces protein, fat, calcium, and ash digestibility, whereas SGIT and IT do not. These results should be taken into consideration when designing diets for humans who have undergone these surgical procedures.

Authors' contribution: MG, SMH, JLR, and FB wrote the paper; MG and FB designed the experiment (digestibility project conception); MG conducted the research; SMH contributed to interpretation of the data, the preparation of the manuscript, and provided supervision support during the whole experimental period. JLR provided technical support being the Veterinary Medical Doctor, responsible for care and health of animals. All authors read and approved the final manuscript.

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