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1 **Intestinal adaptations after bariatric surgery: consequences on**
2 **glucose homeostasis**

3

4 Jean-Baptiste CAVIN¹, André BADO¹ and Maude LE GALL^{1#}

5 ¹Inserm UMR 1149, UFR de Médecine Paris Diderot, Université Paris
6 Diderot, Sorbonne Paris Cité, DHU Unity APHP, F-75890 Paris France

7

8 # Correspondance: maude.le-gall@inserm.fr

9 <http://www.cri1149.fr/>

10

11 **ABSTRACT**

12 The gastrointestinal (GI) tract can play a direct role in glucose homeostasis by
13 modulating the digestion and absorption of carbohydrates and by producing the
14 incretin hormones. In recent years, numerous studies have focused on intestinal
15 adaptation following bariatric surgeries. Changes in the number of incretin-
16 (GLP-1, GIP) producing cells have been reported which could result in the
17 modified hormonal response seen after surgery. Additionally, the rate of
18 absorption and the intestinal regions exposed to sugars may affect the time
19 course of appearance of glucose in the blood. This review gives new insights into
20 the direct role of the GI tract in the metabolic outcomes of bariatric surgery, in
21 the context of glucose homeostasis.

22

23 **KEYWORDS**

24 Intestine, Roux-en-Y gastric bypass, Vertical sleeve gastrectomy,
25 Nutrient flow, Enteroendocrine cells, Glucose transport

26

27

28 **Introduction**

29 Bariatric surgeries were originally developed to treat patients with severe
30 obesity; they were initially recommended for patients with morbid obesity (body
31 mass index (BMI) > 40 kg/m²) or severe obesity (BMI 35.0–39.9 kg/m²) when
32 they exhibited at least one comorbidity that had the potential of being improved
33 by the intervention[1,2]. Today, the two most commonly performed bariatric
34 surgeries worldwide are the Roux-en-Y gastric bypass (RYGB, Figure 1A) and
35 the vertical sleeve gastrectomy (VSG, Figure 1B)[3]. Bariatric surgeries have
36 consistently resulted in significant improvements on obesity-associated
37 metabolic diseases such as type 2 diabetes. This resulted in new
38 recommendations proposing that surgery should be considered for moderately
39 obese diabetic patients (BMI 30.0–34.9 kg/m²) if hyperglycemia is inadequately
40 controlled despite optimal treatment with medication[4,5]. These new
41 recommendations have already been adopted by several medical societies all
42 around the world and should further increase the number of operated patients in
43 the near future. Understanding these surgeries is thus of major clinical and
44 societal importance.

45 The fact that the GI tract is the direct target of bariatric procedures potentially
46 makes it a key player, although so far underestimated, in the metabolic changes
47 observed after surgery. Indeed, the GI tract can play a direct role in glucose
48 homeostasis by modulating gastric emptying, the digestion of carbohydrates and
49 absorption of glucose during meals, and also by secreting a set of hormones,
50 including incretins that regulate the release of insulin[6].

51 In this review, we will outline the GI-dependent mechanisms responsible for the
52 alteration of gut hormone secretion after surgery. Then, we will discuss how
53 intestinal glucose transport (the passage of glucose from the intestinal lumen to
54 the blood compartment through intestinal epithelial cells), and intestinal glucose

55 metabolism are modified after RYGB and VSG, and describe how these changes
56 can affect glucose homeostasis.

57

58 **Altered gut hormone secretion**

59 After bariatric surgeries, changes in the fasting and postprandial secretion of
60 gut-derived hormones are significant and varied and depend on the type of GI
61 reconstruction [7,8]. These changes are suggested to be key players in the
62 increased postprandial secretion of insulin and improved insulin sensitivity that
63 is reported after bariatric surgery.

64 *Glucagon-like peptide 1 (GLP-1)*

65 GLP-1 is an incretin hormone produced by enteroendocrine cells scattered
66 throughout the intestinal epithelium. The density of these GLP-1 secreting cells
67 increases across a proximal to distal gradient. GLP-1 increases insulin release
68 and decreases glucagon production, delays gastric emptying and intestinal transit
69 and reduces meal size [9]. Although fasting concentrations of GLP-1 do not
70 change markedly after bariatric surgery, postprandial levels of GLP-1 have been
71 shown to increase following most, if not all, bariatric procedures [10–13].

72 However, studies designed to evaluate the influence of GLP-1 *per se* on glucose
73 regulation and weight loss, have produced varied results. Mice with genetic loss-
74 of-function of the GLP-1 receptor respond normally to VSG [14] and RYGB
75 [15] in terms of both weight loss and improvements in glucose regulation.

76 Conversely, specific deletion of the GLP-1 receptor in beta cells was shown to
77 prevent the improvement of glucose tolerance in VSG-operated mice [16].

78 Together these studies indicate that GLP-1 alone cannot account for the overall
79 metabolic effect of these two surgeries but may contribute to the altered
80 postprandial glycemic response after VSG in mice. In humans, GLP-1
81 antagonists (exendin-9-39) failed to impair the otherwise improved glucose
82 tolerance after VSG [17] and had only modest effects on glycemic response after
83 RYGB [18,19].

84 *Glucose-dependent insulinotropic polypeptide (GIP)*

85 GIP is another incretin hormone secreted by enteroendocrine cells located mostly
86 in the duodenum and proximal jejunum and released in response to nutrients
87 (notably lipids) [9]. GIP promotes the conversion of glucose to fatty acids and
88 their storage in adipose tissues [20]. While some studies report similar
89 enhancements of GIP secretion following RYGB and VSG surgery [21], others
90 have documented GIP levels to be unchanged [10,22] or reduced
91 [23,24] following RYGB surgery. Although not yet formally demonstrated, it is
92 possible that since GIP is produced by cells of the proximal intestine,
93 differences in the length of the intestinal limb bypassed by the surgery could
94 differentially affect meal-induced GIP secretion in patients. Moreover, the
95 presence or the absence of type-2 diabetes in patients before bariatric
96 surgery might affect the alteration of GIP secretion after surgery [25,26]. A recent
97 study investigated the combined and separate effects of endogenously secreted
98 GLP-1 and GIP on glucose tolerance after RYGB [27]. GLP-1 increased insulin
99 and attenuated glucagon secretion in the postprandial state, whereas
100 amplification of the GIP signal aggravated postprandial hyperglucagonemia and
101 did not contribute to the improved glucose tolerance [27]. The role of GIP in
102 the improved glucose tolerance following RYGB is still an open question and also
103 remains to be addressed in detail in the context of VSG.

104 *Ghrelin*

105 Ghrelin is an orexigenic hormone produced mainly in the stomach and
106 duodenum that exerts gluco-regulatory functions [28]. Resection of the fundic
107 region in VSG leads to a decrease in ghrelin-expressing cells and concomitant
108 ghrelin-circulating levels in rats [29,30] and humans [11,31,32]. Body weight
109 and glucose tolerance measurements after VSG, however, showed similar results
110 in ghrelin-deficient and in wild-type mice [33]. Moreover, while postprandial
111 ghrelin levels are reduced after VSG [11,31,32], they have been reported to
112 either decrease [34], increase [32,35] or remain unchanged [11,36] after RYGB

113 compared to obese patients. Post-operative modifications of ghrelin levels after
114 surgery are, therefore, unlikely to determine metabolic improvement.

115 *Other digestive hormones*

116 Hormones, such as cholecystokinin [10], PYY [37] and others [7], have also been
117 found to be modulated after some bariatric procedures and have thus been
118 proposed as important factors contributing to the post-surgery metabolic
119 improvement. Hormonal changes are certainly involved in the positive outcomes
120 of surgery, but all simplistic views aiming to identify “the” determinant
121 hormone responsible for the beneficial effect of bariatric surgeries are probably
122 shortsighted and futile, since GI surgeries lead to a profound alteration of the
123 entire gut’s hormonal response, following a meal. After surgery, a new
124 homeostatic state is instituted and thus hormone levels should be considered in
125 relation to each other rather than compared to their pre-operative values. For
126 instance, physiologically, glucagon secretion decreases after a meal, but it has
127 been shown that postprandial glucagon release is increased following RYGB
128 and VSG compared to pre-operative states [21,38]. Interestingly, one study
129 reported that GIP, GLP-1, and GLP-2 differently affect glucagon responses to
130 orally ingested glucose in patients with diabetes [39]. Indeed, in non-operated
131 diabetic patients, intravenous infusion of GIP increased the glucagon response
132 and thus counteracted the reduction of glucagon secretion associated with
133 intravenous infusion of GLP-1. Since postprandial levels of GLP-1 and GIP are
134 modified after bariatric surgery, these hormonal interactions could explain how
135 postprandial glucagon levels are increased. Understanding how all these
136 hormonal signals act together to mediate the effects of surgery is an important
137 but ambitious research goal, particularly considering that we are far from
138 understanding how they are integrated together, even in physiological
139 conditions.

140

141 The origin of these modified hormonal secretions is still debated. Historically,
142 altered nutrient flow, either by foregut exclusion or by accelerated hindgut
143 delivery of nutrients, was considered responsible for the improved hormonal
144 response and the success of derivative procedures like RYGB [40]. The modified
145 postprandial hormonal response observed after VSG, a purely gastric surgery in
146 which the food path is not modified, however, has somewhat weakened these
147 assumptions. More recent studies have nevertheless revealed that gastric
148 emptying rates were indeed very rapid after VSG [41–43].

149

150 **Accelerated nutrient flow and increased intestinal surface** 151 **exposure**

152 GI remodeling leads to a drastic acceleration of food arrival in the intestine, by
153 pyloric exclusion after RYGB [12,44] and also by an increase in gastric
154 emptying rate after VSG [42,43]. Increasing evidence shows that the modified
155 dynamics of the nutrient flow is likely to contribute to both the modified
156 glycemic response to a meal and the concomitant altered gut hormone secretion
157 in patients.

158 The total intestinal surface that is almost immediately exposed to a liquid meal
159 is drastically different between operated and control individuals, and affects the
160 entry of glucose into the blood [44]. A study, using radiolabeled tracer, found
161 that only five minutes after a nutrient gavage, the stomachs of RYGB and VSG
162 rats were completely emptied, whereas only 6.1% of the nutrient mixture had
163 emptied from sham animals [41]. The accelerated gastric emptying and food
164 delivery to the intestine increases the total intestinal surface exposed to the
165 luminal content. This could have a direct effect on the rate of glucose entry into
166 the blood during a sugar-rich meal. Indeed, this hypothesis was illustrated by a
167 recent study using multiple intestinal clamp sites in minipigs with RYGB
168 [45]. The study demonstrated a direct relationship between the exposed intestinal
169 area and the transfer of glucose to the blood. More interestingly, the insulin

170 response and secretion of GLP-1 significantly increased only when the total
171 intestinal surface was accessible by the liquid meal. Even if one cannot
172 discriminate whether the stimulation of the distal intestine by the meal or the
173 increase in blood glucose *per se* is responsible for the hormonal response, these
174 experiments suggest that the hormonal response to a meal after RYGB is highly
175 dependent on the altered nutrient flow caused by GI reconstruction.

176 Two human studies confirmed the role of altered nutrient flow in the hormonal
177 response observed after surgery[12,44]. In the first, RYGB patients received
178 either a glucose drink or the same solution infused into the proximal Roux limb
179 at 4 kcal/min, a rate equivalent to physiologic gastric emptying[44]. Blood
180 glucose, insulin, glucagon, GIP and GLP-1 were then measured during the
181 test. The glycemic response was delayed in RYGB patients receiving the solution
182 at 4 kcal/min compared to when the same solution was received orally.

183 Moreover, the infused patients' hormonal responses were similar to those
184 observed in non-operated subjects receiving the oral drink, thus supporting the
185 effect of rapid nutrient exposure on the exaggerated incretin responses. The
186 second study evaluated GI motility with a scintigraphic technique, and gut
187 hormone secretion in RYGB patients [12]. The authors found a statistically
188 significant association between gastric pouch emptying and hormone responses
189 during a multiple meal test. In contrast, no relation was found between gut
190 hormone release and gastric pouch emptying when they used a solid
191 radiolabeled marker, further strengthening the role of rapid nutrient flow in
192 hormone secretion, since transit of solids is much slower than liquids.

193 Interestingly, a study in rats showed that intestinal infusion of a glucose solution
194 at an identical rate led to a greater GLP-1 secretion in VSG rats relative to sham-
195 operated controls [41]. This suggests the existence of delivery-independent
196 mechanisms that alter the gut hormonal response, at least in VSG rats.

197 In summary, the altered glycemic and hormonal response to a liquid meal in
198 RYGB and VSG patients is likely to be mediated by the accelerated nutrient

199 flow after both surgeries, which increases the surface of contact between the
200 meal and the intestine. However, it is worth noting that a mixed meal test may
201 differ in many ways with the daily diet pattern of patients[46] and that
202 the hormonal responses observed experimentally may not occur during small
203 solid meals[47,48].

204 The altered nutrient flow and subsequent modified nutritional stimulation of the
205 intestine after surgery could cause the intestinal adaptation that in turn might
206 affect hormonal secretion and the glycemic response to a meal.

207

208 **Intestinal adaptation and enteroendocrine cell number**

209 Due to the difficulty of directly studying the GI tract of bariatric patients, most
210 of the studies aiming to describe intestinal adaptations after RYGB or VSG
211 procedures have been conducted in experimental models such as rodents. In
212 2009, Stearns et al. were the first to report changes in intestinal structure and
213 function in a rat model of RYGB [49]. They showed an increased villus size and
214 crypt depth in the Roux limb and common limb of operated rats. This
215 hyperplasia has been confirmed and further characterized by several subsequent
216 studies [50–55].

217

218 An important consequence of Roux limb overgrowth after RYGB is an increase
219 in the total number of enteroendocrine cells, including GLP-1-, GIP-, CCK- and
220 PYY-producing cells within the intestinal mucosa[52,54,56,57]. This adaptation
221 was reported in both human and rodent RYGB subjects and could contribute to
222 the modified hormonal profile after surgery. Whether the increased number of
223 enteroendocrine cells due to Roux limb overgrowth is associated with an
224 additional increase in their density, is still a matter of debate[54,57,58].

225

226 To date, no study has directly investigated intestinal adaptation after VSG in
227 humans. However, two recent reports using rat models of VSG described an
228 absence of hypertrophy of the jejunum mucosa after this surgery [54,59].
229 The distribution of enteroendocrine cells producing GLP-1 was also examined in
230 these studies but contradictory results were obtained. The first study reported
231 that GLP-1 cell numbers were not modified at 3 month post-VSG [59]. In
232 contrast, a second study reported an increase in the number and density of GLP-1
233 cells 14 days after surgery [54]. It remains to be determined whether this
234 discrepancy results from the different time points taken for analysis, or
235 differences in other variables such as post-operative diet or surgical
236 techniques. An increase in the density of GLP-1 cells would, however, be a
237 reasonable explanation for the higher delivery-independent GLP-1 secretion
238 observed after VSG in rats [21,37].

239
240 Whether modified numbers of enteroendocrine cells actually affect the release of
241 gut hormone after surgery remains to be determined. An increase in hormone
242 production by or an exacerbated nutrient sensitivity of the enteroendocrine cells
243 after the surgery could also be involved. Assaying the sensitivity of
244 enteroendocrine cells to nutrients before and after surgery will be a challenging
245 task in the future but development of enteroids from human biopsies could offer
246 a unique opportunity to evaluate it [60,61].

247

248 **Intestinal adaptation and glucose transport**

249 The idea that bariatric surgeries could lead to alterations in intestinal glucose
250 transport has been the subject of several studies. To be absorbed by the intestine,
251 polysaccharides must be hydrolyzed into their monosaccharide components
252 (glucose, galactose and fructose) by saccharidases. Glucose and galactose are
253 transported across the apical membrane into the enterocyte by the
254 sodium/glucose cotransporter 1 (SGLT1) [62], whereas fructose is taken up by

255 the fructose transporter 5 (GLUT5)[63]. Monosaccharides are partly
256 metabolized in the enterocytes but most of them exit the cells *via* glucose
257 transporter 2 (GLUT2) in the basolateral membrane, a process that delivers them
258 to the blood before reaching the liver for further metabolism and regulation of
259 glucose production[64]. During sugar-rich meals or in the case of insulin
260 resistance, monosaccharide absorption might be exacerbated after translocation
261 of GLUT2 to the apical membrane [65]. Thus, the appearance of glucose in the
262 blood follows a time course that is affected by the intestinal surface exposed to
263 nutrients, but also by the number of functional enterocytes and the expression of
264 their glucose transporters.

265 Molecular analyses have produced heterogeneous results regarding the
266 expression pattern of intestinal sugar transporters after RYGB in
267 rats[49,51,53,54]. SGLT1, GLUT2 and GLUT5 mRNA or protein levels were
268 reported to be increased[51], decreased [49,51,53] or not modified[54][53] in the
269 alimentary Roux limb of RYGB animals, compared to the jejunum of sham
270 animals. The heterogeneity of these molecular analyses could be due to
271 experimental differences such as different postoperative time points, variable
272 surgical procedures or pre- and post-operative diets. Additionally, the presence of
273 different steps in the adaptive process[54], or alterations in expression levels
274 following diurnal rhythms [49] also likely influence the results. One study
275 reported no difference for SGLT1, GLUT2 or GLUT5 mRNA levels between
276 the Roux limb, the biliopancreatic limb or the common limb of a RYGB minipig
277 model [45]. In humans, increased mRNA expression of SGLT1 and GLUT2 has
278 been reported more than a year after surgery[66]. Thus species-related
279 differences might also exist.

280 It is worth highlighting that the activity of SGLT1 does not always correlate with
281 its mRNA expression [49,54]. The growth of the intestinal mucosa, following
282 RYGB, and therefore the increased numbers of enterocytes could affect the total
283 absorptive capacity of the intestine, beyond the expression of sugar transporters.

284 In fact, it is hard to demonstrate the relationship between transporter expression
285 and the glycemic response to an oral glucose tolerance test *in vivo*. Accordingly,
286 differences in the glycemic response of rats between 14 and 40 days post-RYGB
287 have not been observed despite significant variation in the expression of their
288 intestinal sugar transporters [30]. Direct assessments of intestinal glucose
289 transport capacity before and after surgery are, therefore, still needed to evaluate
290 the existing functional changes.

291 *Ex vivo*, glucose transport can be measured by radioactive methods with isolated
292 intestinal segments from rats that have undergone bariatric surgery. Entry of
293 glucose into the enterocytes (from the mucosal or serosal side) is referred to
294 as intestinal glucose uptake but is often misnamed as intestinal glucose transport,
295 which is actually the passage of glucose from the intestinal lumen to the blood
296 compartment through enterocytes. Of note, in a recent study, no alteration in
297 glucose transport in the Roux limb of RYGB rats compared to the jejunum of
298 sham rats was observed, whereas glucose uptake was markedly increased in
299 RYGB rats regardless of the entry site (mucosal or serosal side) [54]. After
300 RYGB, some studies report a reduction in intestinal glucose
301 uptake [45,49] whereas others report no changes [54,67]. It has also been reported
302 that RYGB may abolish the diurnal rhythm associated SGLT1-mediated glucose
303 uptake, with a 63% reduction specifically prior to the onset of feeding [49].
304 Finally, a study in humans reported that RYGB was followed by an increase in
305 SGLT-1 expression and showed a positive association between SGLT-1
306 expression and glucose absorption [66]. Once again, the methods used to
307 evaluate the glucose uptake, the intestinal segments, and the exact time-points at
308 which measurements were made after surgery differed widely among studies,
309 probably contributing to the heterogeneity of the results.

310 To the best of our knowledge, only one group has evaluated glucose transport
311 and uptake after VSG [54]. In this study, glucose transport from the luminal to
312 the serosal side was markedly decreased in the jejunum of VSG rats, compared

313 to sham-operated rats. Expression of the sugar transporters SGLT1, GLUT2 or
314 GLUT5 did not reflect the modification in intestinal transport capacity. The
315 mechanism of this regulation is still unknown, but VSG could improve glucose
316 tolerance by delaying the entry of alimentary glucose. This would be in
317 agreement with the delayed glycemic response observed after an oral load of
318 glucose in rats [54] or in VSG subjects compared to RYGB subjects [68].
319 It is difficult to transpose these *ex vivo* findings upon what actually happens
320 during a glucose gavage or a meal, since the dynamic aspect of nutrient flow is
321 lost. In addition, whilst intestinal glucose transport may be reflected by the early
322 slope of an oral tolerance test, glucose clearance after the peak is the reflection
323 of glucose disposal by peripheral organs such as liver, muscles and adipose
324 tissue but also, as described below, the intestine itself.

325

326 **Intestinal adaptation and glucose disposal**

327 It has been shown recently that hyperplasia in the Roux limb after RYGB is
328 associated with a reprogramming of glucose metabolism towards increased
329 intestinal glucose uptake and consumption by intestinal cells [53,54]. The
330 remodeled intestine could thus increase wholebody glucose disposal and
331 contribute to the glucose lowering effect of derivative bariatric procedures.
332 The reprogramming of glucose metabolism is characterized by increased mRNA
333 and protein levels of enzymes involved in glycolysis, and by the appearance of
334 the glucose transporter GLUT1 at the basolateral membrane of enterocytes
335 [53,59,54]. The GLUT1 transporter is widely expressed during development but
336 its expression is decreased in adults and becomes very low in mature jejunum
337 [69]. The overexpression of intestinal GLUT1 after RYGB might be a
338 consequence of the increased energy demand to support the intestinal
339 hyperplasia that occurs very early after surgery. Accordingly, there is no
340 reprogramming of glucose metabolism and no overexpression of GLUT1 in the
341 jejunum of VSG-operated rats that does not display any hyperplasia [54,59].

342 *In vivo*, using positron emission tomography-computed tomography (PET-CT)
343 scanning and intravenous administration of [¹⁸F]-FDG, it has been demonstrated
344 that RYGB surgery increases intestinal glucose disposal in rats [53]. Similarly,
345 another study reported increased metabolic activity in the Roux limb of
346 humans following bariatric surgery using the same techniques[54].
347 Considering the contribution of increased intestinal glucose disposal to the
348 glucose lowering effect of RYGB surgery, a study on rats using PET-CT
349 scanning reported a 90% higher [¹⁸F]-FDG uptake by the intestine of RYGB-
350 treated rats and a 30% reduction in [¹⁸F]-FDG signal in the blood, compared to
351 sham animals[53]. This suggests that intestinal glucose utilization is key to the
352 improvement of wholebody glucose disposal in rats. To date, intestinal blood
353 glucose disposal has not been quantified in human patients, but a recent study
354 measured GI retention and presumably metabolism of ingested glucose in obese
355 subjects before and after RYGB [70]. Using a mixed meal containing labeled
356 [^{6,6-2}H₂]-glucose, the authors demonstrated that GI clearance of ingested glucose
357 is increased after RYGB surgery. However, the difference effected by the
358 bariatric procedure was low (from 10% ± 8% before to 15% ± 9% after surgery),
359 showing that intestinal glucose diversion during meals is not likely to largely
360 contribute to the postprandial improvement in glycemic control.
361 Studies directly measuring the intestinal clearance of intravenously
362 administered glucose are needed to evaluate whether the reprogramming of
363 glucose metabolism and subsequent increase in intestinal glucose disposal
364 makes a real contribution to the glucose lowering effect of RYGB surgery in
365 humans.

366

367 **Concluding Remarks and Future Perspectives**

368 Glucose excursion after a meal depends on intestinal transport of glucose to the
369 blood, secretion of gut hormones and glucose handling by peripheral organs.
370 The remodeled GI tract after bariatric surgery plays a major role in altering all

371 these processes. Complementing the associated accelerated nutrient flow and
372 increased intestinal surface exposure, the two main types of bariatric surgeries,
373 RYGB and VSG, differently alter gut morphology, gut hormone secretions, and
374 intestinal glucose transport and metabolism (**Key Figure**) and these factors may
375 all contribute to glucose homeostasis. The biggest challenge now is to evaluate
376 the relative contribution of all these mechanisms (**Outstanding questions box**)
377 and to find a way to recapitulate the important ones in non-surgical or less
378 invasive treatments.

379

380 **FIGURES AND KEY FIGURE**

381 **Figure 1: Two common types of bariatric surgeries**

382 (A) The Roux-en-Y gastric bypass (RYGB) consists of creating a small
383 gastric pouch below the esophagus (25-50mL in humans) that is connected
384 directly to the middle portion of the jejunum, bypassing the rest of the stomach,
385 the pylorus and the upper portion of the small intestine (duodenum and proximal
386 jejunum), which is anastomosed distally. The operation creates three
387 anatomically distinct gut segments: an alimentary limb (or Roux limb), which
388 receives only undigested food (red arrows); a biliopancreatic limb, which drains
389 gastric secretions, bile and pancreatic enzymes (blue arrows); and a common
390 limb that connects the two aforementioned limbs together. This operation is very
391 efficient, with an important and sustained weight loss accompanied by a
392 reduction in obesity-associated comorbidities such as hypertension,
393 hyperlipidemia and type 2 diabetes in most patients. (B) The vertical sleeve
394 gastrectomy (VSG) involves a longitudinal resection of the stomach starting
395 from the antrum and ending at the fundus close to the cardia; the remaining
396 volume of the gastric compartment is about 150 mL in humans. This
397 intervention has been proven to be an effective procedure at middle term with an
398 important weight loss accompanied by a reduction in obesity-associated

399 comorbidities such as hypertension, hyperlipidemia and type 2 diabetes in many
400 patients.

401

402 **Figure 2, Key Figure: Differential intestinal adaptations after RYGB versus**
403 **VSG and their putative contributions to the resulting altered hormone**
404 **secretion and improved glucose tolerance.**

405 Both bariatric surgeries reduce the transit time of the meal and increase the
406 exposure of the intestinal mucosa that acts to modify secretion by enteroendocrine
407 cells and also glucose entry. In response to RYGB, the Roux limb becomes
408 hyperplastic, with the number of incretin secreting cells increasing. Additionally,
409 a shift in glucose metabolism increases the intestinal glucose consumption. In
410 response to VSG, despite no intestinal hyperplasia, the number of GLP-1
411 positive cells may increase due to increased cell density. Moreover, studies in
412 rats suggest that glucose transport from the lumen to the blood decreases
413 delaying alimentary glucose absorption. To date, no study has directly
414 investigated intestinal adaptation after VSG in humans.

415

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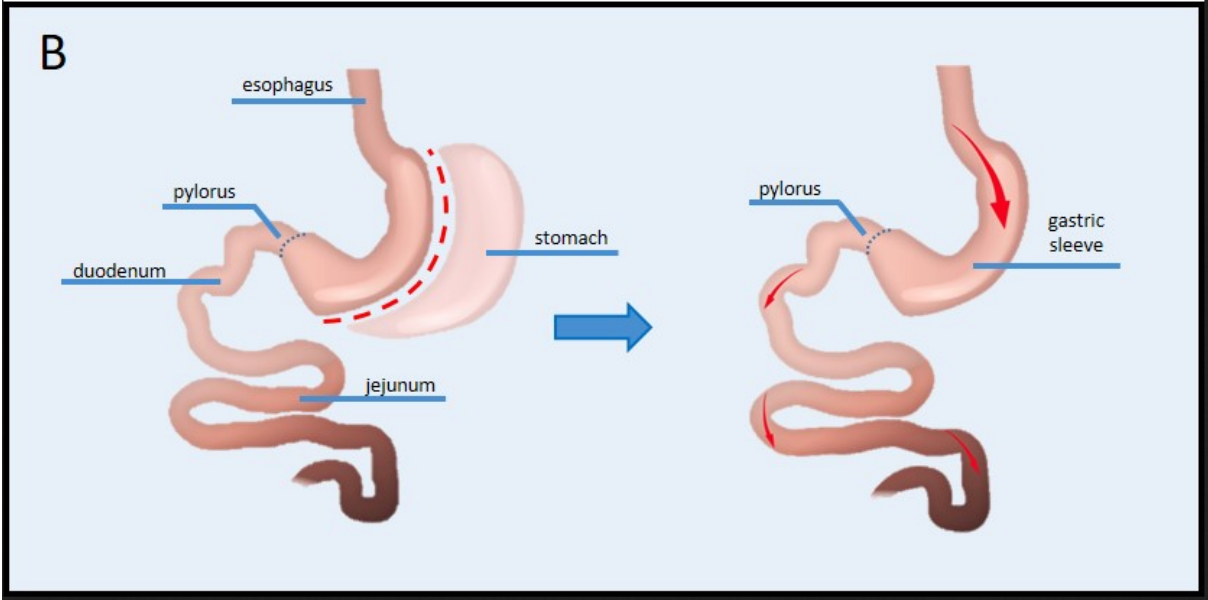
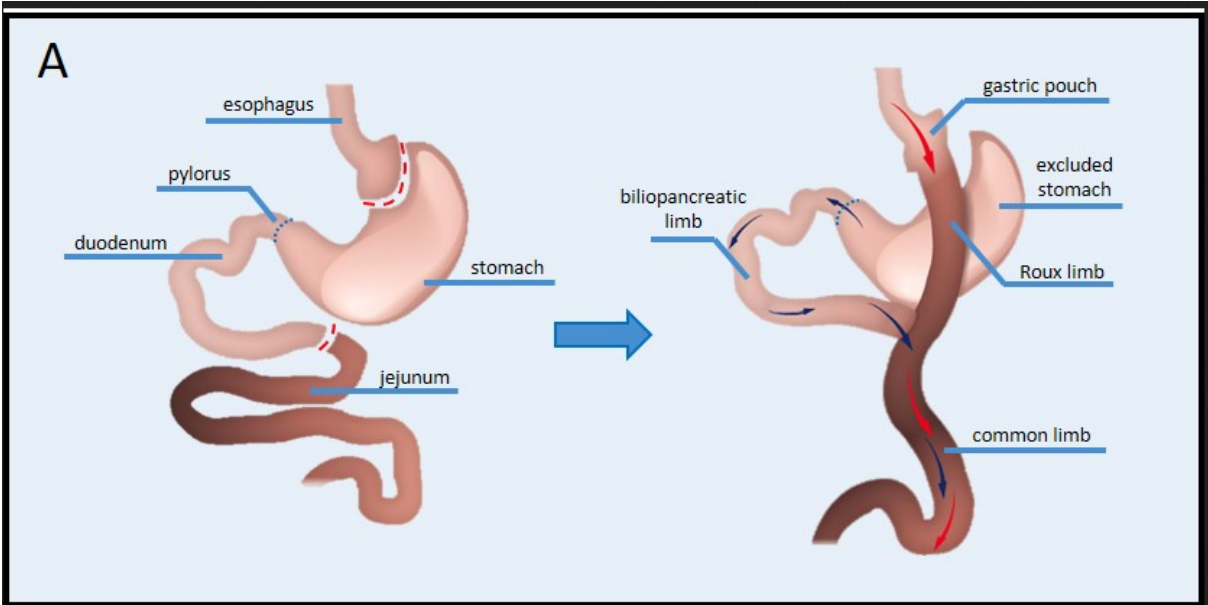


Figure 1A,B

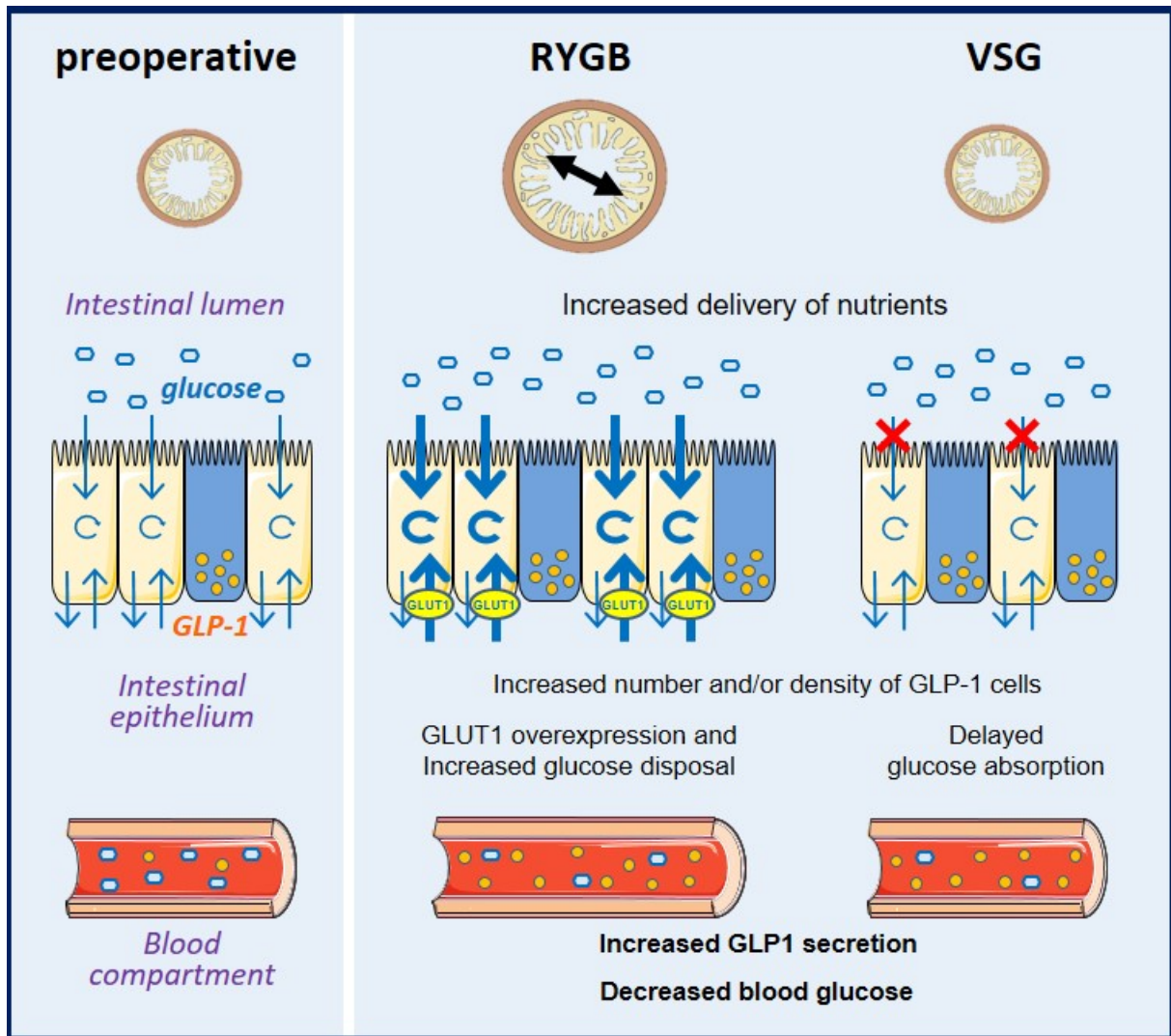


Figure 2