Gastric bypass increases energy expenditure in rats

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Postprint available at:
http://www.zora.uzh.ch

Originally published at:
Title: Gastric bypass increases energy expenditure in rats

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**Grant support:** M. B. was supported by the Deutsche Forschungsgemeinschaft (DFG). T.L. and C.L. were supported by the Swiss National Research Foundation. S.B. and C.le R. were supported by a Department of Health Clinician scientist award. Imperial College London receives support from the NIHR Biomedical Research Centre funding scheme. M.W. was supported by the Markin Undergraduate Student Research Program. K.A.S. is an Alberta Heritage Foundation for Medical Research Medical Scientist and receives support from Canadian Institutes of Health Research.

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**Disclosure:** The authors have no conflict of interest to disclose.
Abstract

Background

Mechanisms underlying weight loss maintenance after gastric bypass surgery are poorly understood. Our aim was to examine the effects of gastric bypass on energy expenditure in rats.

Methods

Thirty diet-induced obese male Wistar rats underwent either gastric bypass (n=14), sham operation ad libitum fed (n=8) or sham-operation body weight-matched (n=8). Energy expenditure was measured in an open circuit calorimetry system.

Results

Body weight after 70 days was lower after gastric bypass compared to sham ad libitum fed rats (p<0.0001). Sham-operated body weight-matched controls ate less than gastric bypass animals to reach the same weight (16.2±0.5g vs. 27.5±0.8g, p<0.001). Twenty-four hour energy expenditure was increased after gastric bypass (4.50±0.04 kcal/kg/h) compared to sham-operated ad libitum fed (4.29±0.08 kcal/kg/h) and sham-operated body weight-matched controls (3.98±0.10 kcal/kg/h, p<0.001). Gastric bypass rats showed higher energy expenditure during the light phase than both sham-operated control groups (sham ad lib: 3.63±0.04 kcal/kg/h vs. sham body weight-matched: 3.42±0.05 kcal/kg/h vs. bypass: 4.12±0.03 kcal/kg/h, p<0.001). Diet-induced thermogenesis was elevated after gastric bypass compared to sham-operated body weight-matched controls three hours after a test meal (0.41±1.9% vs. 10.5±2.0%, p<0.05). The small bowel of gastric bypass rats was
72.1% heavier due to hypertrophy compared with sham-operated ad libitum fed rats (p<0.0001).

Conclusions

Gastric bypass surgery in rats prevented the expected decrease in energy expenditure subsequent to weight loss. Diet-induced thermogenesis was higher after gastric bypass compared to body weight-matched controls. Raised energy expenditure may be an additional mechanism explaining the physiological basis of weight loss after gastric bypass surgery.

Keywords

gastric bypass; weight loss; energy expenditure; diet induced thermogenesis, gut hypertrophy
Background and Aims

The obesity epidemic is a major health concern that is associated with increased morbidity and mortality \(^1\) as well as negative personal, social, and economic consequences \(^2,3\). Roux-en-Y gastric bypass (gastric bypass) is the most effective therapeutic option currently available for sustained weight loss with a proven mortality benefit \(^4,5\). Gastric bypass procedures are increasing rapidly \(^6\), but underlying mechanisms by which gastric bypass induces and sustains weight loss are poorly understood. Initially, it was speculated that weight loss after gastric bypass was due to mechanical restriction and malabsorption \(^7\). Experimental and clinical studies, however, have suggested that other mechanisms contribute to weight loss after gastric bypass \(^8-13\). The absence of a compensatory increase in appetite after gastric bypass-induced weight loss has been intriguing, because non-surgical intentional body weight loss is usually followed by body weight regain through increased appetite \(^14\).

A proposed mechanisms for reduced food intake after bypass surgery is the secretory stimulus to L-cells in the distal gut, resulting in increased levels of gastrointestinal satiation hormones such as peptide YY (PYY) and peptides of the enteroglucagon family \(^9,11,15-17\). These hormones stimulate anorectic pathways in the hypothalamus and brainstem leading to reduced food intake \(^18\) and may also influence energy expenditure \(^19\).

Gastric bypass surgery has been successfully modeled in rat experiments. The body weight loss after gastric bypass in rats is not only due to decreased food intake, as sham-operated pair-fed controls weigh more than gastric bypass rats \(^10,11,20-22\). Possible explanations such as malabsorption and inflammation have been excluded.
10, thus the weight difference despite similar food intake raises the possibility of
enhanced energy expenditure 10 as previously speculated 23,24. We therefore tested
the hypothesis that energy expenditure would be higher after bypass surgery.
Methods

Animals and housing

Thirty adult diet-induced obese male Wistar rats weighing 480 – 500 g were used for energy expenditure experiments, and sixteen adult male Wistar rats weighing 330-350 g were used for morphometric gut analysis. All animals were individually housed under artificial 12 hour / 12 hour light-dark cycle and at a room temperature of 21±2ºC unless otherwise stated. Water and standard chow were available ad libitum. All experiments were performed under a license issued by the Home Office UK (PL70-6669) or were approved by the Veterinary Office of the Canton Zurich, Switzerland.

Surgery

Surgery was performed according to an established protocol as described in the supplementary information. Figure 1 shows a schematic illustration of the pre- and postoperative anatomy.

Indirect calorimetry

Measurements were conducted in an open circuit calorimetry system (AccuScan Inc., USA) as described in the supplementary information.

Experimental design
The thirty diet-induced obese rats used in the energy expenditure experiments were randomized to gastric bypass (n=14) or sham operation (n=16). After a recovery period of 7 days sham-operated animals were randomly divided into two groups of 8 rats each: shams with no dietary manipulation (ad libitum fed shams weighing 488.8±3.9 g) and food-restricted shams whose postoperative weight was matched to the weight of bypass animals (body weight-matched shams weighing 474.3±4.2 g). Starting on day 7 after gastric bypass surgery, the body weight-matched shams received as much food daily as was necessary for them to maintain a similar body weight to the bypass rats. Based on experiences from previous studies, rats were given 10 g of standard chow in the beginning of food restriction. This amount of food was offered at dark onset and readjusted every third day depending on the body weight. Sixteen metabolic cages were used and measurements were conducted in the following order on three consecutive days: bypass (n=8) vs. sham ad libitum fed (n=8) (40 days after surgery) and bypass (n=6) vs. shams body weight-matched (n=8) (75 days after surgery). Diet-induced thermogenesis was measured in rats that were fasted for 12 hour from the beginning of the light cycle and received a 5 g meal at subsequent dark onset. Diet-induced thermogenesis was calculated as the cumulative increase in energy expenditure after a 5 g test meal compared to fasting values before the test meal (expressed as percentage of the energy content of the test meal: 17.6 kcal). Methods for faecal and blood analysis are described in the supplementary material.

Measurement of Body composition
Adipose tissue mass was measured using a rodent CT scanner (Latheta, Aloka, Japan). Rats were anesthetized with isoflurane and the area between vertebrae L1 and L5 was scanned using an X-ray source tube voltage of 50 kV, current of 1 mA, pitch size of 2 mm, and a speed of 4.5 sec per image (roughly 25 images per rat). Aloka© software was used to estimate volumes of adipose tissue and non-adipose tissue using differences in X-ray density. Adipose tissue weights were computed using the density factor of 0.92 g/cm³. Scanning was undertaken seventy days after surgery.

**Gut morphometry**

For the study of gut morphometry 16 male Wistar rats were randomized to gastric bypass (n=8) or sham operation (n=8). All rats were ad libitum fed throughout the complete observation period of 60 days. Rats were fasted for 24 hours before being killed to ensure the small bowel was free of chow residue. The entire small bowel from the duodenum to the ileocaecal valve was collected. Total wet weight and length of the small bowel were measured in the sham-operated rats, whilst in gastric bypass rats the weight and length of the three limbs (alimentary, biliopancreatic and common channel) were measured separately and then added. Supplementary material describes gut tissue processing and analysis.

**Statistical analysis**

All data were normally distributed and are expressed as mean ± SEM. Student’s t-test for independent samples and one-way ANOVA with repeated measures and
post-hoc Bonferroni test for each time point were used to test for significant
differences. P<0.05 was considered significant. For all analyses data from the two
gastric bypass groups were pooled, because data did not differ between the two time
points (day 40 and day 75 after surgery).
Results

Body weight

Figure 2 shows the body weight changes for both groups. For the energy expenditure experiments (figure 2a), body weight was significantly lower in gastric bypass rats compared to the sham-operated ad libitum fed group from day 5 after surgery. On postoperative day 70, the difference in weight was almost 200 g (sham ad lib: 603.2±6.6 g vs. bypass: 414.3±13.8 g, p<0.0001). After a short period of postsurgical weight loss, shams ad libitum fed constantly gained weight for the rest of the study. In contrast, gastric bypass animals lost 11.2±1.4% of their preoperative weight by postoperative day 10; body weight then plateaued around 415 g.

Food restriction started one week after surgery for the body weight-matched shams (n=8). There was no significant difference in body weight between the gastric bypass group and the food restricted body weight-matched rats on and after day 55 (sham body weight-matched: 412.2±3.0 g vs. bypass: 408.7±9.4 g, p=0.78).

There was no increase in either fresh faecal mass (sham ad lib: 8.4±0.5 g vs. sham body weight-matched: 6.6±0.6 g vs. bypass: 7.3±0.4 g, p=n.s.) or faecal calorie content (sham ad lib: 3.56±0.04 kcal/g vs. sham body weight-matched: 3.51±0.04 kcal/g vs. bypass: 3.65 ± 0.04 kcal/g, p=n.s.) in the gastric bypass animals compared to the control groups. C-reactive protein levels were below the detection limit of the assay (<2mg/L) in all animals suggesting no postsurgical infection or inflammation 28 days after surgery.

In the gut morphometry experiments, body weight was significantly lower in gastric bypass rats compared to the sham-operated group from day 5 after surgery (figure
sham-operated rats gained weight for the rest of the study, while gastric bypass animals lost 15.4±1.1% of their preoperative weight by postoperative day 10 and then plateaued around 260 g. The difference in body weight on day 60 was 164 g (sham ad lib: 423.6±10.2 g vs. bypass: 259.1±16.3 g, p<0.0001).

**Body Composition**

Adipose tissue mass between vertebrae L1 and L5 in gastric bypass was lower than in sham-operated ad libitum fed rats, but similar to body weight-matched shams (sham ad lib: 27.6±2.7 g vs. sham body weight-matched: 5.3±0.9 g vs. bypass: 11.6±1.3 g, p<0.001). Non-adipose tissue in gastric bypass was lower than in sham ad libitum fed rats, but higher than in body weight-matched shams (sham ad lib: 107.1±2.9 g vs. sham body weight-matched: 71.0±1.1 g vs. bypass: 80.9±2.4 g, p<0.001).

**Food intake outside metabolic cages**

Food intake followed similar patterns as body weight. Figure 3a shows the average daily food intake for rats of the energy expenditure experiments (postoperative day 1-70). Daily food intake was consistently lower after gastric bypass (sham ad lib: 34.0±1.2 g vs. bypass: 27.5±0.8 g, p<0.0001). Body weight-matched shams required significantly less food than gastric bypass animals to maintain the same level of body weight (sham body weight-matched: 16.2±0.5 g vs. bypass: 27.5±0.8 g, p<0.0001). Gastric bypass rats used for the analysis of gut morphometry also ate significantly
less than their sham-operated counterparts (sham: 32.5±0.4 g vs. bypass: 26.0±0.5 g, p<0.0001).

Food intake in metabolic cages

Meal patterns were different between the three groups in the energy expenditure experiment. In the dark phase gastric bypass and sham-operated ad libitum fed rats ate more than in the light phase. Dark phase food intake in gastric bypass rats was lower than in sham ad libitum fed rats (sham ad lib: 26.6±1.1 g vs. bypass: 17.0±1.5 g, p<0.0001), while they ate more during the light phase (sham ad lib: 2.7±0.5 g vs. bypass: 4.5±0.7 g, p<0.05, Figure 3b). Sham-operated body weight-matched rats consumed all their food during the first half of the dark phase and are therefore not represented in figure 3b.

Energy Expenditure

Twenty four hour energy expenditure was increased after gastric bypass compared to sham-operated ad libitum fed rats and sham-operated body weight-matched controls (sham ad lib: 4.29±0.08 kcal/kg/h vs. sham body weight-matched: 3.98±0.10 kcal/kg/h vs. bypass: 4.50±0.04 kcal/kg/h, p<0.001). Sham body weight-matched rats had lower total energy expenditure than sham-operated ad libitum fed rats (p<0.05). When analyzing the two phases of the light dark-cycle separately, it was obvious that during the light phase, when overall activity is typically low, energy expenditure in gastric bypass rats was significantly higher than in sham-operated ad libitum fed animals and body weight-matched shams (sham ad lib: 3.63±0.04 kcal/kg/h vs. sham
body weight-matched: 3.42±0.05 kcal/kg/h vs. bypass: 4.12±0.03 kcal/kg/h, p<0.001). In the dark phase, when overall activity is typically higher, there was no difference in energy expenditure between gastric bypass and sham-operated ad libitum fed rats, but energy expenditure in bypass rats was higher than in body weight-matched shams (sham ad lib: 4.81±0.06 kcal/kg/h vs. sham body weight-matched: 4.46±0.15 kcal/kg/h vs. bypass: 4.81±0.04 kcal/kg/h, p<0.01). Figure 4a shows average 24 hour, light phase and dark phase energy expenditure for all groups.

Respiratory Quotient

Respiratory quotient was examined during 12 hours of fasting and for the subsequent 6 hours after offering a fixed test meal of 5 g. Results are shown in figure 4b. During fasting gastric bypass rats had a lower respiratory quotient than sham-operated ad libitum fed rats, but there was no difference to sham-operated body weight-matched rats. The pattern was similar for the 0-3 hour observation period after the test meal for gastric bypass, sham ad libitum fed and sham body weight-matched rats (sham ad lib: 0.89±0.01 vs. sham body weight-matched: 0.78±0.01 vs. bypass: 0.77±0.01, p<0.001) and the 3–6 hour observation period after the test meal (sham ad lib: 0.95±0.01 vs. sham body weight-matched 0.73±0.01 vs. bypass: 0.74±0.01, p<0.001). Respiratory quotient between gastric bypass and sham body weight-matched rats was not different during fasting or the six hours after the test meal.

Body Temperature
Body temperature as measured during the light and dark phase is shown in Figure 4c. Body temperature in gastric bypass rats was lower than in sham-operated ad libitum fed rats, but higher compared to body weight-matched sham rats during the light phase (sham ad lib: 36.8±0.02°C vs. sham body weight-matched: 36.3±0.06°C vs. bypass: 36.5±0.03°C, p<0.001). During the dark phase, average body temperature in gastric bypass rats was lower than in sham-operated ad libitum fed rats, but no different compared to body weight-matched sham rats (sham ad lib: 37.7±0.02°C vs. sham body weight-matched: 37.3±0.09°C vs. bypass: 37.3±0.03°C, p<0.001).

**Physical activity**

A dissociation between total energy expenditure and body temperature was observed and thus, physical activity was analyzed (Figure 4d). No difference in activity over 24 hour or during the light phase was seen among all three groups. During the dark phase, however, gastric bypass rats were less active than sham-operated ad libitum fed rats and sham-operated body weight-matched rats (sham ad lib: 7.19±0.4 activity counts vs. sham body weight-matched: 6.70±0.8 activity counts vs. bypass: 5.04±0.2 activity counts, p<0.001).

**Diet-Induced Thermogenesis**

Diet-induced thermogenesis was measured over three hours after a 5 g standard test meal after a 12h fast. The sham-operated ad libitum fed and the sham-operated body weight-matched groups consumed all 5 g within 20 minutes, the gastric bypass
animals required 30 minutes. Figure 4e shows the diet-induced thermogenesis for all
groups for the first three hours after the test meal. Three hours after the 5 g test
meal, gastric bypass rats had a significantly greater diet-induced thermogenesis than
the body weight-matched controls, but bypass was not different from the sham-
operated ad libitum fed rats (sham ad lib: 5.2±4.4% vs. sham-body weight-matched:
0.41±1.9% vs. bypass: 10.5±2.0%, p<0.05).

Gut morphometry

Differences in gut morphometry are summarized in figure 5. There was no difference
in total length of the complete small bowel between sham-operated and gastric
bypass rats (sham ad lib: 108.6±1.7 cm vs. bypass: 110±2.2 cm, p=0.8). In contrast,
the wet weight of the small bowel was 72.1% higher after gastric bypass than after
sham-operations (sham ad lib: 12.2±0.6 g vs. bypass: 21.0±1.2 g, p<0.001). Average
weight of the alimentary limb was 10.6±0.8 g, of the biliopancreatic limb 2.7±0.2 g
and of the common channel 7.8±0.6 g. Muscle thickness (sham ad lib: 95.0±8.7 µm
vs. bypass: 247.9±32.5 µm, p<0.001), mucosal height (sham ad lib: 530.8±19.1 µm
vs. bypass: 969±58.2 µm, p<0.001), villus height (sham ad lib: 390.4±21.7 µm vs.
bypass: 673.6±63.8 µm, p<0.001) and crypt depth (sham ad lib: 140.4±8.0 µm vs.
bypass: 295.4±20.6 µm, p<0.001) were significantly increased in the alimentary limb
after gastric bypass in comparison to the corresponding section of the jejunum of the
sham-operated controls. Gastric bypass rats had a significantly greater villus height
of the common channel than sham-operated animals (sham ad lib: 287.1±18.1 µm
vs. bypass: 464.6±73.9 µm, p<0.05). There was a trend towards an increase in
mucosal height (sham ad lib: 490.4±29.6 µm vs. bypass: 673.8±99.7 µm, p=0.09)
and muscle thickness (sham ad lib: 490.4±29.6 µm vs. bypass: 673.8±99.8 µm, p=0.09) in the common channel.
Discussion

Our data in the rat gastric bypass model are consistent with previous findings that gastric bypass surgery is effective to reduce body weight and especially to maintain body weight loss \cite{4,9,10,12,16}. We confirmed that body weight loss after gastric bypass was associated with a significant loss of fat mass and to a lesser degree of non-adipose body mass \cite{28,29}. Food intake was reduced in gastric bypass rats which may be partly explained by hormonally mediated mechanisms \cite{9,16,30}. Importantly, the lower food intake after gastric bypass compared with sham-operated ad libitum fed rats only partly explains body weight loss, because the sham-operated body weight-matched group required on average 40% less food than the bypass group to maintain the same level of body weight. Consequently, reduced calorie consumption is important but not the sole cause of weight loss after gastric bypass. We found no increased fecal mass, fecal calorie content or inflammation in the gastric bypass animals; therefore nutrient malabsorption or inflammation are unlikely to play a major role in this weight loss \cite{10}.

We demonstrate a higher total energy expenditure in rats after gastric bypass compared to ad libitum fed and body weight-matched sham groups which is in accordance with some, but not all previous reports of energy expenditure in humans \cite{31-33}. Our differences in energy expenditure were mainly due to changes during the light phase when physical activity is typically low. Gastric bypass surgery did not only prevent the expected decrease in energy expenditure subsequent to body weight loss, but actually increased 24 hour and in particular light phase energy expenditure in comparison to the control groups.
Higher energy expenditure after gastric bypass was associated with lower respiratory quotients suggesting that fat rather than carbohydrates was burnt to sustain higher energy expenditure. However, food restricted body weight-matched controls showed similar respiratory quotient levels to the gastric bypass group suggesting that body weight loss rather than a specific effect by the gastric bypass procedure was an important determinant for the observed decrease in respiratory quotient.

As higher levels of total energy expenditure usually result either from greater heat generation or increased physical activity, some of our findings remain unexplained. Firstly, bypass rats were not more physically active than the control groups. The bypass rats showed no difference in spontaneous activity during the light phase to indicate reduced sleep time, but we have not formally evaluated sleep patterns. In fact, at least during the dark phase, when spontaneous activity is usually high, physical activity was lower in the bypass rats than in the sham controls. As gastric bypass induces an increase in postprandial levels of PYY and GLP-1 which reduce food intake, the reduced dark phase physical activity may possibly indicate reduced appetite and hence less foraging or food seeking behaviour. The second unexpected finding was the lower body temperature in gastric bypass rats compared to ad libitum fed sham controls. This was observed throughout the light-dark cycle. However, during the light phase the body temperature of the gastric bypass rats was higher than in the body weight-matched controls despite no difference in physical activity. It must be emphasized that during the light phase gastric bypass rats continued to consume some food, whilst the body weight-matched shams consumed all food during the first half of the dark cycle. Thus, differences in light phase body
temperature might be related to food intake and subsequently diet-induced
thermogenesis \(^{35,36}\).

After a 5 g test meal gastric bypass rats had greater diet-induced thermogenesis than
body weight-matched controls, but no difference was observed between gastric
bypass rats and the ad libitum fed sham group.

Our data suggest that gastric bypass induces profound changes in food intake,
energy expenditure and the mechanisms by which the body controls energy
expenditure. As gastric bypass significantly rearranges the gastrointestinal anatomy,
we suggest that gastrointestinal and central neuroendocrine signaling contribute to
increased energy expenditure \(^{34}\). Neurons in the hypothalamic arcuate nucleus
(ARC) co-express neuropeptide Y (NPY) and agouti-related peptide, which stimulate
food intake and weight gain \(^{37}\). Another population of ARC neurons co-express pro-
opiomelanocortin (POMC) and cocaine-and-amphetamine-regulated transcript
(CART), which both promote weight loss \(^{38}\). The balance between NPY and POMC is
critical for the maintenance of body weight \(^{37-39}\). Gastric bypass increases
postprandial levels of PYY and GLP-1 \(^{9,10}\), which are satiating inducing gut hormones
and hence favour an anorectic state and facilitate body weight loss through
modulation of the hypothalamus and brainstem \(^{40,41}\), also being involved in the
control of energy expenditure \(^{18}\). In fact, PYY has been shown to activate anorectic
POMC expressing neurons in the ARC \(^{42}\) and to inhibit NPY neurons \(^{43}\), suggesting a
potential to increase energy expenditure.
Gastrointestinal effects of GLP-1 and PYY can be resolved by ablation of vagus–brainstem–hypothalamus pathways indicating a role for the vagus in mediating effects on food intake and potentially energy expenditure. However, it was beyond the scope of this study to assess the potential role of vagal or visceral neural afferent information to the central nervous system.

GLP-1 increases endogenous amylin levels. Amylin may be another potential candidate decreasing food intake and increasing energy expenditure. Of note, the reduced food intake after amylin is independent of GLP-1 and vice versa (Lutz TA, unpublished data). Nonetheless, chronic amylin administration reduces food intake and it prevents the decrease in energy expenditure that would typically result from lower food intake and body weight loss (Lutz TA, unpublished data).

The increase in total energy expenditure might also represent a higher energy requirement after bypass surgery. We also demonstrated significant morphometric changes of the small intestine after gastric bypass surgery. The observed increase in muscle thickness and mucosal mass after gastric bypass resulted in a 72% increase of the total small bowel weight. The gut is metabolically very active and the mean in vitro rates of oxygen consumption in gastrointestinal tissues in rats have been reported to be 15-22% of total oxygen consumption. Thus, gut hypertrophy may at least in part explain the higher maintenance energy requirement that contribute to body weight loss.
Postoperative inflammation secondary to infection can lead to a higher energy demands, but we found no evidence of an inflammatory response in our study. Other mechanisms that should be considered but may be less likely include decreased leptin after gastric bypass. Usually high leptin and not low leptin contributes to increased energy expenditure \(^{50}\). Although low leptin levels may explain the lower body temperature in bypass rats than in ad libitum fed controls, it does not explain the observed difference in body temperature between bypass and body weight-matched rats.

This study does not explain why average body temperature was reduced while total energy expenditure was higher after gastric bypass. One possible explanation is that more heat was dissipated to the immediate environment of the rats especially since gastric bypass rats had significantly less body fat and hence less thermal isolation. We did not assess cutaneous vasodilation to further explore potential mechanisms. Another explanation may be an up regulated activity of brown adipose tissue, but our measuring system did not allow the separate assessment of brown adipose tissue and tail temperature..

In summary, not only did gastric bypass surgery prevent the expected decrease in energy expenditure subsequent to body weight loss in this diet-induced obese rat model, but 24 hour and in particular light phase energy expenditure were higher than in sham controls. Diet-induced thermogenesis was also higher after gastric bypass surgery compared to body weight-matched controls. Increased energy expenditure
may offer an additional explanation why gastric bypass surgery is superior to dieting for successfully maintaining long-term body weight loss.
Acknowledgements

We gratefully acknowledge the help of Dr. Jacquelien Hillebrand (ETH Zürich) and Manuela Munz for measurement of body composition and Winnie Ho for assistance with the histology.
Figures

Figure 1

(a) Stomach

(b) Stomach

Pouch

A

10 cm

B

50 cm

C

25 cm

D
Figure 2

(a) BW [g] vs. postop days

(b) BW [g] vs. postop days
Figure 3a and b

![Graph a: Food Intake (g) vs. Phase]

**Figure 3b**

![Graph b: Food Intake (g) vs. Phase]

Legend:
- ***: Significant difference
- *: Significant difference

**x-axis:** light phase, dark phase
**y-axis:** Food Intake [g]
Figure 4

a) Energy Expenditure [kcal/kg]

b) Respiratory Quotient

c) Body Temperature [°C]

d) Activity count (AC)

e) Diet-induced thermogenesis [%]
Legends

Figure 1
Diagrammatic representation of the gastrointestinal anatomy before (a) and after (b) the gastric bypass operation. (A) Biliopancreatic limb (~ 10 cm), (B) Alimentary limb (~50 cm), (C) Common channel (~25 cm), (D) Coecum.

Figure 2
Body weight change for the gastric bypass (-o-) (n=14) and sham-operated rats ad libitum fed (-■-)(n=8) and sham-operated body weight-matched (-●-)(n=8) used for energy expenditure measurements (a) and for gastric bypass (-o-) (n=8) and sham-operated rats ad libitum fed (-■-)(n=8) used for gut morphometry analysis (b). Data are shown as mean values ± SEM.

Figure 3
(a) Average daily food intake over 70 days for sham-operated ad libitum fed rats (n=8, white column), for sham-operated body weight-matched rats (n=8, grey column) and for gastric bypass rats (n=14, black column). Data are shown as mean values ± SEM (** *= p<0.001).

(b) Average food intake during dark and light phase for sham-operated ad libitum fed (n=8, white columns) and gastric bypass rats (n=8, black columns). Data are shown as mean values ± SEM (* = p<0.05, *** = p<0.001).

Figure 4
Differences in maintenance energy expenditure (a), respiratory quotients (b), average body temperature (c), activity (d) and diet-induced thermogenesis (e) for sham-operated ad libitum fed (n=8, white columns), for sham-operated body weight-matched (n=8, grey columns) and for gastric bypass rats (n=14, black columns). While data for energy expenditure, body temperature and activity are shown during 24 hour, the light and dark phase, respiratory quotients are shown during 12 hour fasting and within the first six hours after a 5g test meal. Data for diet-induced thermogenesis are expressed as a percentage of the energy content of a 5g test meal and shown at 1h, 2h and 3h after re-feeding with the test meal after a 12 hour fasting period. All data are shown as mean values ± SEM (* = p<0.05, ** = p<0.01, *** = p<0.001).

Figure 5

Length (a) and weight (b) of the entire small bowel and differences in gut morphometry in rats 60 days after gastric bypass (n=8) and sham operation (n=8). Differences in muscle thickness (c), mucosal height (d), villus height (e) and crypt depth (f) are shown for the alimentary limb, the biliopancreatic limb and the common channel after gastric bypass in comparison to the corresponding parts of jejunum, duodenum and ileum after sham-operation. Data are shown as mean values ± SEM (*** = p<0.001, * = p<0.05).
References


