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ORIGINAL CONTRIBUTIONS

Influence of Energy Balance on the Rate of Weight Loss Throughout One Year of Roux-en-Y Gastric Bypass: a Doubly Labeled Water Study

Michele Novaes Ravelli[1,2] · **Dale A. Schoeller**[3] · **Alex Harley Crisp**[1] · **Timothy Shriver**[3] · **Eduardo Ferriolli**[4] · **Carlos Ducatti**[5] · **Maria Rita Marques de Oliveira**[6]

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Abstract

Objective To investigate the influence of changes in energy balance and body composition on the rate of weight loss throughout 1 year of Roux-en-Y gastric bypass.

Methods Variables were collected pre-, 6, and 12 months (M) post-surgery from 18 women (BMI ≥ 40 and ≤ 50 kg m^{-2}, 20 to 45 years). Total energy expenditure (TEE$_m$), fat-free mass (FFM), and fat mass (FM) were measured by doubly labeled water. Self-reported energy intake (EI$_{sr}$) was obtained from three non-consecutive food diaries. Metabolic adaptation was assessed via deviations from TEE predictive equation, and the calculated energy intake (EI$_c$) via the sum of TEE and change in body stores.

Results BMI significantly decreased (mean ± SD) from 45 ± 2 kg m^{-2} to 32 ± 3 kg m^{-2} at 6 M, and to 30 ± 3 kg m^{-2} at 12 M after surgery. The TEE$_m$ reduced significantly at both time points when compared with pre-surgery (6 M: − 612 ± 317 kcal day^{-1}; 12 M: − 447 ± 516 kcal day^{-1}). At 6 M, a metabolic adaptation was observed and the energy balance was − 1151 ± 195 kcal day^{-1}, while at 12 M it was − 332 ± 158 kcal day^{-1}. Changes in the values of TEE$_m$ were associated with changes in body weight at 12 M post-surgery. A significant underreporting was observed for EI$_{sr}$ (1057 ± 385 kcal day^{-1}) vs. EI$_c$ (2083 ± 309 kcal day^{-1}) at 12 M post-operative.

Conclusion The higher rate of weight loss at 6 M post-surgery was a response to energy imbalance, which was caused by high restriction in energy intake even with the presence of metabolic adaptation at this time. The EI$_{sr}$ was not sufficiently accurate to assess the energy consumption of this population.

✉ Michele Novaes Ravelli
ravelli@neurology.wisc.edu

Dale A. Schoeller
dschoell@nutrisci.wisc.edu

Alex Harley Crisp
alexhcrisp@gmail.com

Timothy Shriver
tshriver@wisc.edu

Eduardo Ferriolli
eferriol@fmrp.usp.br

Carlos Ducatti
cie.ibb@unesp.br

Maria Rita Marques de Oliveira
maria-rita.oliveira@unesp.br

[1] School of Pharmaceutical Sciences, Sao Paulo State University – UNESP, Rodovia Araraquara Jaú, Km 01, s/n. Bairro: Campos Ville, Araraquara, SP 14800-903, Brazil

[2] Department of Neurology, University of Wisconsin – Madison, 1685 Highland Avenue, Medical Foundation Centennial Building, 7th Floor, Madison, WI 53705, USA

[3] Biotechnology Center, University of Wisconsin – Madison, 425 Henry Mall Street, Madison, WI 53706, USA

[4] Ribeirao Preto Medical School, University of Sao Paulo – USP, Avenida Bandeirantes, 3900 - Bairro: Monte Alegre, Ribeirão Preto, SP 14049-900, Brazil

[5] Stable Isotope Center, Bioscience Institute, Sao Paulo State University – UNESP, Rua Prof. Dr. Antônio Celso Wagner Zanin, 250 - Bairro: Distrito de Rubião Junior, Botucatu, SP 18618-689, Brazil

[6] Education Department, Institute of Biosciences, Sao Paulo State University – UNESP, Rua Prof. Dr. Antônio Celso Wagner Zanin, 250 - Bairro: Distrito de Rubião Junior, Botucatu, SP 18618-689, Brazil

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Keywords Bariatric surgery · Energy balance · Body composition · Metabolic adaptation · Doubly labeled water

Introduction

Obesity persists as a serious and difficult to control public health problem accompanied by a complex etiology. According to the World Health Organization [1], the worldwide prevalence of obesity has almost tripled between 1975 and 2016. Thus, the search for effective treatments, such as surgical procedures, also showed an increase in global demand, from 40,000 in 1997 to 468,609 in 2013 [2]. Among the types of bariatric surgery, Roux-en-Y gastric bypass (RYGB) has the best success rates [3]; however, it is estimated that a portion of bariatric patients (37%) regain part of the weight lost (21–29%) [4]. These observations have led some researchers to speculate that the key to the weight regain could be an adaptive decrease in energy expenditure while others speculate it is due to an increase in energy consumption.

RYGB induces a large weight loss due to the reduction of the gastric chamber volume and intestinal deviation. This results in restriction of food consumption, decreased nutrient absorption, and alterations in the neural networks of the digestive system thus causing changes in the release of hunger and satiety hormones [3, 5].

The regulation of energy metabolism after bariatric surgery has not been sufficiently studied regarding a smaller than expected weight loss and/or weight regain after surgery. While some researchers [6, 7] suggest that the restriction in energy consumption caused by surgical treatment may alter diet-induced thermogenesis and, consequently, total energy expenditure (TEE), others disagree [8, 9]. In addition, poor adherence to post-surgical nutrition therapy, the presence of unhealthy eating patterns, and a progressive increase in total energy intake could also partly explain any change in the pattern of weight loss or weight regain following surgery [10, 11].

Changes in body composition after bariatric surgery have also been associated with a non-adaptive reduction in the energy expenditure, more specifically in resting energy expenditure (REE) [8, 12]. Among body compartments, fat-free mass (FFM) is considered to be more metabolically active than fat mass (FM). Nonetheless, FM contributes to an increase in energy expenditure as a whole in the obese state as this tissue mass increases considerably more than FFM. This in turn leads to an increase in REE (kcal/day) when compared with the values of individuals with healthy weight [13, 14]. Any change in energy expenditure can also be influenced by two opposite mechanisms related to obesity: an increase in TEE caused by a greater body mass or a decrease of TEE caused by the difficulty in performing physical activities in the presence of excess weight [13, 14].

Considering the possibility of metabolic alterations caused by changes in body composition, energy imbalance, hormonal changes, and surgical interaction [14] and taking into account the high number of patients whose weight loss following bariatric surgery is limited, the aim of this study was to investigate the influence of changes in the components of energy balance (energy expenditure vs. energy intake) and in body composition throughout 1 year following bariatric surgery.

Subjects and Methods

Study Design

A longitudinal clinical study was conducted with patients serving as their own control. TEE, physical activity energy expenditure (PAEE), self-reported energy intake (EI_{sr}), and anthropometric data were measured. All these parameters (mean ± SD) were measured pre-surgery (31 ± 13 days before surgery), 6 months post-RYGB (189 ± 5 days after surgery), and 12 months post-RYGB (373 ± 1 days after surgery) (Table 1). To minimize variability, all data was collected by the same investigator during visits to the Brazilian public health clinic that assisted the patients. During the first visit of each data collection phase, the study protocol and data to be collected were verbally reviewed. On the second visit, baseline urine samples were collected for isotopic analysis and an oral dose of doubly labeled water (DLW) was given for the measurement of TEE and body composition. The dose of DLW for each period of the study was calculated from the average total body water (TBW) of the participants as measured by a bioimpedance (InBody 230; BioSpace, Seoul, South Korea) [15]. The DLW was pre-weighed (± 0.01 g) averaging 144 g for pre-surgery, 101 g for 6 months post-surgery, and 85 g for 12 months post-surgery. The DLW was administered orally followed by two 50-mL rinses of the cup with water.

Demographic and anthropometric information was obtained on the second visit. At this time, participants were also instructed and trained to adequately fill a 24-h food diary for a three non-consecutive day period as well as to proper use of an accelerometer. Participants were advised to use this device for 14 days while keeping their normal physical activity routine and remove it only during bathing and physical activities involving water. At the third visit (15 days after the second

Table 1 Description of the methodological procedures developed in each phase of the study

Pre-surgery	1st visit • Invitation to participate in research • Signing of the informed consent form • Verbal and written guidelines for the second visit
	2nd visit • Urine (baseline) • Doubly labeled water dose (TEE and body composition) • Guidelines for urine collection at home for 14 consecutive days • Anthropometric information • Guidelines for adequate completion of the 24-h food diaries • Guidelines for proper use of the accelerometer
	3rd visit • Collection of urine samples at home by patients • Participant meeting with registered dietitian to review the 24-h food diaries • Accelerometer pickup
6 and 12 months post-surgery	1st visit • The reminder of the date, time, and preparation for the procedures of the second visit
	2nd visit • Same as pre-surgical visit 2
	3rd visit • Same as pre-surgical visit 3

visit), urine samples, food diaries, and accelerometers were collected and reviewed by the investigator (Table 1).

Subjects

Twenty-two women with class III obesity, who were waiting for bariatric surgery, were consented and approved by the local research ethics committee (protocol number: 306.538), and entered into the study. Inclusion criteria were age between 20 and 45 years, reproductive system active (non-menopausal period), body mass index (BMI) from 40 to 50 kg/m^2; absence of edema assessed by Godet's sign, diseases known to alter energy metabolism (e.g., diabetes mellitus, hypothyroidism, HIV infection, cancers, heart, kidney and liver diseases), and use of medicine with metabolic and absorptive effects (e.g., diuretics, amphetamines, thyroid hormones, topiramate, orlistat, and corticosteroids). Two patients were excluded due to withdrawal at 6 months post-operatively, and two additional patients at 12 months post-operatively due to isotopic analysis results that failed quality control checks. Eighteen participants completed all components of the study which provides the data analyzed here.

Self-reported Energy Intake (EI_{sr})

For each period of data collection, the 24-h food diaries were obtained on three non-consecutive days: two during the week and one on the weekend. The household measures [16, 17] of the daily consumption of foods, beverages, and food supplements (protein, vitamins, and minerals) were tabulated. The EI_{sr} was calculated based on the food consumption database of the Brazilian population [18], or based on the nutritional composition of the supplements mentioned in the food diaries.

Anthropometry and Body Composition

Body weight and height measurements were obtained under standardized conditions and through a scale coupled to the InBody 230® bioimpedance instrument and SECA® vertical anthropometer, respectively. The data were collected in the morning, with patients wearing light clothing and without shoes, after an 8-h fast. BMI was calculated by body weight (kg) divided by height (m) squared.

The amount of FM and FFM was calculated by means of the stable isotope dilution technique and according to the protocol proposed by Schoeller [19] and validated by Tylavsky et al. (2003) [20]. After the ingestion of DLW and equilibration of the isotopes with the body water, the dilution space of the DLW was calculated through previously published equations [19], and then, FFM was calculated using the adult mammalian hydration constant (73.2%). To calculate FM, the FFM was subtracted from the total body weight.

Measured Total Energy Expenditure (TEE_m)

Total energy expenditure was calculated by the validated method [19] of elimination of isotopically labeled water in body water. The DLW method considers that the isotope deuterium oxide (^{2}H) is eliminated as water and the isotope oxygen-18 (^{18}O) as water and CO_2. Differences in the elimination rates of these two isotopes over the time are proportional to the rate of CO_2 production [19]. A dose of 2 g per kg of body water of ^{18}O with 10.8 at.% and 0.12 g per kg of body water of ^{2}H with 99.8 at.% was offered to each participant for oral consumption. Urine samples, collected before, within 4 h, and 14 days after the dose ingestion were analyzed in triplicate via isotope ratio mass spectrometer (Hydra 20-20 and Hydra 20-22, Europe Scientific—Cheshire/UK models) at the Ribeirao Preto Medical School, University of Sao Paulo. The multiple-point protocol and TEE equations proposed by Schoeller [19] were used. Carbon dioxide production was calculated assuming a dilution space ratio of 1.035 and TEE calculated assuming a respiratory quotient of 0.86.

Metabolic Adaptation

To investigate if a metabolic adaptation in TEE_m occurred, and to subsequently determine if it was due to changes in body composition and/or the difference in the performance of physical activity using the number of steps as a predictor, the values of pre-surgery TEE_m were used in the elaboration of a predictive equation of TEE (TEE_p) following the approach described by Knuth et al. [21]. We considered FM (kg), FFM (kg), age (years), and the number of steps (S) adjusted by current body weight (BW) in kilograms ($S \times W$) in multiple linear regression:

$$\begin{aligned} TEE_p = 1354.3 &+ (9.8 \times \text{FFM}) \\ &+ (7.3 \times \text{FM}) - (12.6 \times \text{age}) \\ &+ (0.0011 \times [S \times \text{BW}]) \end{aligned}$$

This equation presented a positive correlation ($r^2 = 0.678$, $p = 0.003$) between the measured and predicted TEE values from the pre-surgery time point. The predictive equation of TEE was then applied at the 6 and 12 post-operative months. A significant negative residual was used as evidence of the presence of metabolic adaptation in these periods.

Calculated Energy Intake (EI_c)

Energy intake was calculated using the principle of energy balance described by Racette et al. (2012) [22] and validated by Gilmore et al. (2014) [23]. This equation estimates energy intake with a slight underestimation of actual EI by 0.2–3.8% through the variation of TEE and the storage of body energy over time [23].

$$EI_c = TEE_{adj} + \left(\frac{\text{BES}}{\text{td}}\right)$$

where EI_c is the value of energy intake calculated in kcal/day, TEE_{adj} is the total energy expenditure adjusted at 6 or 12 months after surgery in kcal/day as described below, BES is the value of body energy stores lost during the weight loss process in kcal, and td is the exact number of total days between the periods of measurements.

Because we had less frequent measures of TEE than did those authors [22] and the highest weight loss was during the first 6 months post-surgery, we assumed, based on the data from those authors, that energy expenditure would drop rapidly after the onset of weight loss and thus could be approximated by TEE at 3 months using TEE measured at 6 months but adjusting for the loss of FFM and FM between pre-surgery and 6 months post-surgery:

$$\begin{aligned} TEE_{adj\ 3M} = \text{TEE } 6m + 9.8 \times \left(\frac{\Delta\ \text{FFM}}{2}\right) + 7.3 \\ \times \left(\frac{\Delta\ \text{FM}}{2}\right) \end{aligned}$$

where the values 9.8 and 7.3 are constants obtained in the equation to predict TEE for the participants of this study, described in the metabolic adaptation section. The delta (Δ) values are the difference of FFM and FM between the pre-surgery and 6 months post-surgery. For the period of 6 and 12 months, the TEE_{adj} was considered the average between the TEE measured at 6 and 12 months post-surgery.

The BES was calculated from the difference of FFM and FM between the periods of measurements and, then, multiplied by the energy density of these tissues:

$$\begin{aligned} \text{BES} = &[(\text{FM}_{n+1} - \text{FM}_n) \times 9500] \\ &+ [(\text{FFM}_{n+1} - \text{FFM}_n) \times 1100] \end{aligned}$$

where $'n+1'$ and $'n'$ are the values at 1st period: 6 months post-surgery ($n+1$) and pre-surgery (n); 2nd period: 12 months ($n+1$) and 6 months (n) post-surgery. The energy density was 9500 kcal/kg for FM and 1100 kcal/kg for FFM [24].

Physical Activity Energy Expenditure

A triaxial accelerometer (ActiGraph model GT3X+, Pensacola, FL, USA) was attached to the participants' waist (right side) and was calibrated for each subject, using ActiLife 6 Software (ActiGraph, Pensacola, FL, USA). In each of the three data collection periods, the patients had their physical activities monitored for 14 days, being advised to keep their normal physical activity routine while wearing the device. The participants were instructed to remove the device only during bathing and physical activities involving water. The data collected by the accelerometer were transferred and processed in 60-s epochs with ActiLife 6 software.

To obtain the device wear time, Troiano et al.'s [25] validation algorithm was applied to activity counts from the vertical axis. Non-wear time was defined as the sum of periods of 60 or more consecutive minutes of continuous zero counts with a tolerance of up to 2 min of activity counts between 0 and 100 counts per minute. Wear time was calculated by subtracting the non-wear time within 24 h. The data from the triaxial accelerometer was only considered valid if there was a minimum of 10 h of its usage per day.

To estimate the PAEE from activity counts, we applied the algorithm described by Sasaki et al. [26], which uses vector magnitude counts per minute (VMCPM) of the three axes. The vector magnitude (VM) calculation is valid when the VMCPM is higher than 2453.

$$\text{kcal/min} = 0.001064 \times \text{VM} + 0.087512(\text{BW}) - 5.500229$$

where:

VM vector magnitude = $\sqrt{\text{axis1}^2 + \text{axis2}^2 + \text{axis3}^2}$
BW body weight in kg

Bariatric Surgery

The RYGB is described as a supraumbilical median laparotomy (public health in Brazil allows only open bariatric surgeries), in which a gastric reservoir of small curvature (8 × 3 cm) was made by a 75-mm mechanical suture [27]. There was a reconstruction of the Roux-en-Y transit with a biliary limb at 40 cm from the Treitz angle and 150 cm Roux limb in precolic position [27]. Two levels of end-to-side gastrojejunal anastomosis (1.5 cm) were manually performed. As a mold, 3–0 polydioxanone continuous suture with Faucher 11 esophageal probe in transanastomotic position was used [27].

Statistical Analyses

Statistical analyses were conducted using IBM SPSS Statistics software (Version 21.0, Armonk, NY: IBM Corp.). The variables were verified by the Kolmogorov-Smirnov normality test and presented as mean and standard deviation (SD) and/or median and quartiles (1st and 3rd). The change (Δ) values (difference of the mean) were calculated for all dependent variables.

A one-way ANOVA test followed by the Bonferroni adjustment was performed for comparative analysis of the variables of body composition, energy expenditure, and energy intake, for the time points of the study. The interaction between the changes in the delta values of the variables of the study was evaluated by linear regression analysis, using changes in the delta values of the TEE_m from the preoperative time point as the dependent variable.

A paired *t* test was used to compare measured and predicted TEE values and predicted energy intake. Metabolic adaptation was considered present when the residual values between measured and predicted TEE after surgery were negative and significant by Friedman's test followed by the Student-Newman-Keuls adjustment. A *p* value of < 0.05 was considered significant for all statistical analyses.

Results

Table 2 shows changes in body composition, energy expenditure, and energy intake during the first year after bariatric surgery. A significant weight loss of − 31.3 ± 4.3 kg (≅ − 27%) occurred at 6 months post-operatively and − 38.2 ± 6.2 kg (≅ − 33%) at 12 months post-operatively. FFM was − 5.3 ± 2.1 kg (− 10%; $p < 0.05$) at 6 months post-operatively compared with pre-surgery; the FFM was not significantly different at 12 months post-operatively (− 0.7 ± 3.8, − 2%) compared with the 6 months post-operative value. FM was reduced significantly by − 26 kg and − 32 kg at the 6 and 12 post-operative months, respectively, which corresponded to a − 12% and − 17% change in percentage of fat at these times. The total weight loss compared with pre-surgery was composed of 17% and 16% FFM, at 6 and 12 months post-operatively, respectively.

The TEE_m at 6 months post-operative (TEE_m = 2292 ± 430 kcal day^{-1}) was significantly reduced (Δ TEE_m = − 612 ± 317 kcal day^{-1}; − 21%) when compared with pre-surgical values (TEE_m = 2904 ± 547 kcal day^{-1}), and then tended (insignificantly) upwards (Δ TEE_m = 246 ± 530 kcal day^{-1}; + 11%) at 12 months (TEE_m = 2538 ± 336 kcal day^{-1}) compared with 6 months post-operative (Table 2). The values of TEE_p showed a similar pattern, with a significant reduction (Δ TEE_p = − 445 ± 384 kcal day^{-1}; − 15%) at 6 months post-operative when compared with pre-surgical values; however, it did not differ significantly (Δ TEE_p = − 26 ± 153 kcal day^{-1}; − 1%) at 12 months in relation to 6 months post-operative.

The difference in the number of steps was significant by period; however, the PAEE was significantly reduced (Δ PAEE = − 284 ± 346 kcal day^{-1}; −28%) after 6 months post-operative (PAEE = 719 ± 202 kcal day^{-1}) when compared with pre-surgical values (PAEE = 1003 ± 389 kcal day^{-1}) and remained stable until the end of the study (Table 2).

The EI_{sr} was significantly decreased at 6 months after surgery (− 515 ± 521 kcal day^{-1}; − 36%), remaining unchanged at the end of the study period (Table 2). However, EI_{sr} was significantly different from EI_c . The EI_c was significantly higher at 12 months after surgery compared with 6 months. The average energy deficit calculated from the BES was − 1151 ± 195 kcal day^{-1} between the baseline and the 6 months, and − 332 ± 158 kcal day^{-1} between the 6 and 12 months post-surgery results.

The predicted values of TEE based on body composition and number of steps corrected by current body weight did not

Table 2 Body composition, energy expenditure, and energy intake, before and after bariatric surgery ($n = 18$)

Variables	Pre-surgery (T0)	6 months (T1)	12 months (T2)	p*	Δ T1–T0	Δ T2–T1
Body composition						
Body weight (kg)	112.6 ± 7.3^{a}	81.3 ± 7.1^{b}	74.4 ± 7.4^{c}	< 0.001	− 31.3 ± 4.3	− 6.9 ± 2.8
BMI (kg/m^2)	45 ± 2^{a}	32 ± 3^{b}	30 ± 3^{c}	< 0.001	− 12 ± 2	− 2.7 ± 1.0
FFM (kg)	54.2 ± 4.7^{a}	48.9 ± 4.6^{b}	48.1 ± 4.6^{b}	< 0.001	− 5.3 ± 2.1	− 0.7 ± 3.8
FM (kg)	58.4 ± 5.9^{a}	32.4 ± 7.0^{b}	26.1 ± 6.4^{c}	< 0.001	− 26.0 ± 4.3	− 6.3 ± 3.4
FM (%)	52 ± 3^{a}	40 ± 6^{b}	35 ± 6^{c}	< 0.001	− 12 ± 4	− 5 ± 4.0
Energy						
TEE_m (kcal day^{-1})	2904 ± 547^{a}	2292 ± 446^{b}	2538 ± 336^{b}	0.010	− 612 ± 317	246 ± 530
TEE_p (kcal day^{-1})	2897 ± 449^{a}	2452 ± 307^{b}	2426 ± 365^{b}	0.001	− 445 ± 384	− 26 ± 153
PAEE (kcal day^{-1})	1003 ± 389^{a}	719 ± 202^{b}	764 ± 268^{b}	0.013	− 284 ± 346	45 ± 196
Number of steps	7669 ± 2964	8396 ± 2856	9549 ± 4008	0.239	727 ± 3250	1153 ± 2138
Number of steps × body weight (kg)	$8.7 \times 10^5 \pm 3.7 \times 10^5$	$6.9 \times 10^5 \pm 2.5 \times 10^5$	$7.1 \times 10^5 \pm 3.1 \times 10^5$	0.169	$-1.9 \times 10^5 \pm 3.4 \times 10^5$	$2.5 \times 10^4 \pm 1.5 \times 10^4$
EI_{sr} (kcal day^{-1})	1430 ± 432^{a}	$915 \pm 291^{b,A}$	$1057 \pm 385^{b,A}$	< 0.001	− 516 ± 568	142 ± 350
EI_c (kcal day^{-1})	–	$1261 \pm 393^{a,B}$	$2083 \pm 309^{b,B}$	< 0.001**	–	822 ± 337

BMI, body mass index; *FFM*, fat-free mass; *FM*, fat mass; TEE_m, measured total energy expenditure; TEE_p , predicted total energy expenditure based on pre-surgery TEE_m relationship with body composition and number of steps adjusted by actual body weight; *PAEE*, energy expenditure in physical activity; *PAL*, physical activity level; EI_{sr}, self-reported energy intake; EI_c, calculated energy intake between baseline and 6 months and between 6 and 12 months; Δ, difference between time point 6 months (T1), 12 months (T2), and pre-surgery time point (T0). *ANOVA followed by the Bonferroni adjustment. Means followed by the same lowercase letters do not differ significantly at the 5% level by the Bonferroni test to compare the three periods. **Paired *t* test, where mean followed by the same lowercase letters do not differ significantly at the 5% level between the time point of the study, and followed by the same uppercase letters do not differ significantly at the 5% level between the self-reported and calculated energy intake, in the same time point of the study

differ significantly from the measured values of TEE in each of the evaluated periods (Table 3).

There was, however, a significant difference in residual values between TEE_m and TEE_p (Table 4). A metabolic adaptation was evidenced at 6 months post-surgery in which the median of TEE residual value was significantly different from zero, but this was no longer evident at 12 months post-surgery (Table 4).

Table 5 presents the results of the association between the mean differences (Δ values) of the variables studied at 6 and 12 months, respectively. Regression analysis suggests that the changes in body composition, and physical activity between pre-surgery and 6 months post-surgery were not associated with changes in TEE_m in this period. However, the changes of TEE_m occurring between 6 and 12 months post-surgery and reduction in body weight ($\beta = 90.8$; $r^2 = 0.24$; $p = 0.04$) were associated, explaining 24% for the change, but there was no association with changes in body composition and physical activity.

Discussion

Understanding the changes in the components of energy balance after bariatric surgery and their relationship to weight loss and its components (FFM and FM) provides insight into the mechanisms associated with post-surgical weight loss. These factors help identify which factors predominate at 6 and 12 months after surgery may aid in the development of effective strategies for weight loss and its maintenance in bariatric patients. Our results suggest the main driver of weight loss was the reduction of the EI_c following surgery.

Acting in opposition to the reduction in the EI_c, we observed a hypometabolism in the patients at 6 months post-surgery, which is likely caused by metabolic adaptation induced by the negative energy balance due to the restriction of energy intake. However, 1 year after the surgical procedure, the hypometabolism was no longer observed in the

Table 3 Measured and predicted values of TEE and at 6 and 12 months after bariatric surgery

	TEE (kcal/day)	Mean ± SD	p value*
Pre-surgery	TEE_m	2904 ± 547	0.922
	TEE_p	2897 ± 449	
6 months	TEE_m	2292 ± 446	0.194
	TEE_p	2452 ± 307	
12 months	TEE_m	2538 ± 336	0.335
	TEE_p	2426 ± 365	

TEE_m, measured total energy expenditure; TEE_p, predicted total energy expenditure based on pre-surgery TEE_m relationship with body composition and the number of steps adjusted by actual body weight; *p value**, paired *t* test

Table 4 Metabolic adaptation at 6 and 12 months after bariatric surgery

	Period	Mean ± SD	Median (1°; 3° quartiles)	*p* value*
TEE residual (kcal day^{-1})	Pre-surgery	7 ± 311	28[a] (− 129; 180)	$p = 0.017$
	6 months	− 159 ± 500	− 239[b] (− 428; − 49)	
	12 months	112 ± 478	157[a] (− 125; 384)	

TEE_m, measured total energy expenditure; *TEE_p*, predicted total energy expenditure based on pre-surgery TEE_m relationship with body composition and number of steps adjusted by actual body weight; *TEE residual*, TEE_m – TEE_p for each period of the study; *p value**, Friedman's test followed by the Student-Newman-Keuls adjustment. Medians followed by the same letter do not differ significantly at the 5% level by the post hoc test

participants as evidenced by an increase in the value of TEE_m in relation to the TEE_p value. As such, we evidence that the decrease in the value of TEE_m at 6 months compared with pre-surgery was related to a reduction in body size, a reduction in the thermic effect of meals (TEM), and a metabolic adaptation. The increase in TEE_m at 12 months compared with 6 months may be reflective of an increase in TEM secondary to greater EI_c and a reversal of the metabolic adaptation secondary to a less or negative energy balance induced by the increase of energy consumption assessed by the EI_c during this time period.

Changes in body size and the losses of FM and FFM did not fully explain the 20% reduction in measured TEE_m at 6 months post-surgery from the linear regression test. This decrease was similar to the previously reported 18% [28] and 25% [8, 12] reductions in TEE, but these reports showed an association between the decrease in TEE with a significant decrease in FFM. Our results suggest that the lack of association between changes in body composition and significant reduction of TEE_m at 6 months post-surgery can be explained by metabolic adaptation independent of pre-surgical weight and body composition [29]. This is consistent with the expectation that adaptation occurs in response to changes in energy balance, in which negative energy balance results in energy saving as a biological defense or homeostatic response to reduce weight loss due mainly to changes in REE and TEM [29, 30]. At 12 months post-surgery, the metabolic adaptation was no longer apparent. Changes in values of TEE_m, from 6 to 12 months post-surgery, were again associated with changes in body weight. Specifically, means that the increase in the Δ value of TEE_m was associated with the lower lost-weight Δ value, and the converse is true. However, there was no association between changes in TEE_m with changes in FFM, which is strongly associated with changes in the component of energy expenditure [29, 31] as it is expected for this metabolically active tissue [32].

The absence of any increase in daily steps taken by the study participants after the bariatric surgery is inconsistent with the suggestion that post-surgical patients increasing their physical activity [33]. We found that any increase in steps was a subtle and insignificant change that was not enough to promote an increase in PAEE. Instead, we found the PAEE decreased which was related to the significant changes in body weight. Due to the reduction of body weight load during physical activities, energy cost reduces significantly [34] leading to the decrease of the TEE of the patient.

The metabolic adaptation induced by restriction in food consumption was significant at 6 months post-operatively, but was not possible to discern if this was due to RYGB promoting anatomical and physiological changes, the large negative energy balance, or both [14]. The EI_c showed a large restriction in the energy consumption at 6 months post-operatively, but we could not discern if this was due to factors such as reduced digestion and nutrient malabsorption, changes in hunger and satiety, or both during this period [35, 36]. Between 6 and 12 months after surgery, the participants showed a 71% reduction in the magnitude of the energy deficit compared with the 0 to 6 months period and metabolic adaptation no longer detected in this period. This increase in EI_c is likely the main cause of the lower rate of weight loss, described in this and other studies [28, 37].

The results of this study again emphasize the presence of underreporting of energy intake in a population with obesity [38], which again raises the issue regarding a confounding of scientific findings based on EI_{sr} [39]. For example, the EI_{sr} at 12 months post-surgery was similar to the value described at 6 months post-surgery, which does not explain the lower rate of weight loss at 12 months. Nevertheless, the EI_c was significantly higher than EI_{sr} and a more reasonable explanation of the rate of weight loss based on the energy deficit/balance, and is similar to that reported by Wolfe et al. [28].

Even though the energy restriction and physiological changes caused by the surgery can lead to a negative metabolic adaptation at 6 months post-surgery, it was interesting that, at 1 year post-surgery, a metabolic adaptation was no longer observed in the participants, which is not in agreement with results reported from "The Biggest Loser" study which showed metabolic adaptation at 6 years after an intensive diet and exercise intervention [40], even though our participants continued to lose some weight between 6 and 12 months. Similar results to those of our study have also been described by other researchers [21, 28], strengthening the argument that the differences in energy metabolism between the "Biggest Loser" and

Table 5 Associations between changes in body composition and energy variables at 6 and 12 months after RYGB surgery

	Δ TEE_m (kcal day^{-1})					
	Δ T1–T0			Δ T2–T1		
	β	R^2	p	β	R^2	p
Δ Body weight (kg)	30.8	0.17	0.09	90.8	0.24	0.04
Δ FFM (kg)	22.5	0.02	0.56	36.3	0.07	0.39
Δ FM (kg)	24.9	0.11	0.17	32.4	0.04	041
Δ PAEE (kcal day^{-1})	0.30	0.15	0.11	− 0.4	0.02	0.58
Δ Steps × weight	0.00	0.14	0.12	− 0.0	0.10	0.21

FFM, fat-free mass; *FM*, fat mass; *PAEE*, physical activity energy expenditure from accelerometry; EI_{sr}, self-reported energy intake; *Δ*, difference between time point 6 months (T1) or 12 months (T2) and pre-surgery time point (T0); *steps × weight*, number of steps corrected by weight in kg; *p*, linear regression analysis

bariatric surgery studies could be a reflection of the distinct methods of weight loss [28].

Our data in this study suggest that future investigations into the efficacy of bariatric surgery include TEE and its requisite components (PAEE and TEM) in as much as we have identified these elements may be utilized to influence the results of the treatment.

This study has limitations including (i) the small number of subjects, even though it is important to note that clinical studies using the DLW methodology often considers a small number of participants [41] mainly due to cost; (ii) only female participants, which is justifiable considering that 80% of patients who elect bariatric surgery are women [42]; the presence of female participants also helped to achieve the ideal number of participants who satisfied our eligibility criteria for inclusion/exclusion; (iii) the absence of REE data measured by indirect calorimetry is important since studies strongly discuss the correlation between changes in REE and FFM after bariatric surgery [8, 12] which was unintentional due to equipment failure; (iv) the low precision of EI_c for the value at 6 months post-surgery is includes an approximation in which we assumed a linear change over time, since we did not have a measurement of TEE between pre- and 6 months post-surgery; and (v) the final important limitation is the absence of a control weight loss group, which could help to answer whether the metabolic adaptation is a consequence of the RYGB and/or weight loss by clinical treatment; however, it is known that clinical treatment for obesity does not achieve the substantial changes in body weight as the surgical treatment does [43].

Conclusion

In conclusion, our results show that a higher rate of weight loss occurred during the first 6 months post-surgery in response to the energy imbalance caused by a high restriction in energy intake, even with the presence of metabolic adaptation at this time. However, from 6 to 12 months post-surgery, a slower rate of weight loss may be associated with higher energy intake, since the metabolic adaptation was no longer apparent during this period. Recognizing the influences over the rate of weight loss after bariatric surgery may provide insight into the mechanisms associated with weight loss and support the advancement of effective strategies for the maintenance of results.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent The study protocol was approved by the Ethical Committee of the Medical School of Botucatu of the State University of São Paulo, UNESP. Informed consent was obtained from all participants included in the study.

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