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ORIGINAL CONTRIBUTIONS

Development and Validation of a Predictive Model of Success in Bariatric Surgery

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Abstract

Purpose There are no criteria to establish priority for bariatric surgery candidates in the public health system in several countries. The aim of this study is to identify preoperative characteristics that allow predicting the success after bariatric surgery.

Materials and Methods Four hundred and sixty-one patients submitted to Roux-en-Y gastric bypass were included. Success of the surgery was defined as the sum of five outcome variables, assessed at baseline and 12 months after the surgery: excess weight loss, use of continuous positive airway pressure (CPAP) or bilevel positive airway pressure (BiPAP) as a treatment for obstructive sleep apnea (OSA), daily number of antidiabetics, daily number of antihypertensive drugs, and all-cause mortality. Partial least squares (PLS) regression and multiple linear regression were performed to identify preoperative predictors. We performed a 90/10 split of the dataset in train and test sets and ran a leave-one-out cross-validation on the train set and the best PLS model was chosen based on goodness-of-fit criteria.

Results The preoperative predictors of success after bariatric surgery included lower age, presence of non-alcoholic fatty liver disease and OSA, more years of CPAP/BiPAP use, negative history of cardiovascular disease, and lower number of antihypertensive drugs. The PLS model displayed a mean absolute percent error of 0.1121 in the test portion of the dataset, leading to accurate predictions of postoperative outcomes.

Conclusion This success index allows prioritizing patients with the best indication for the procedure and could be incorporated in the public health system as a support tool in the decision-making process.

Keywords Bariatric surgery · Roux-en-Y gastric bypass · Waiting list · Public health · Waiting time · Scoring system

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Introduction

Obesity is a major risk factor for noncommunicable diseases and its prevalence has substantially increased in the past decades, leading to a reduced life expectancy worldwide [1–3]. Bariatric surgery has emerged as an effective treatment for sustained weight loss and long-term improvement in obesity-related diseases [4, 5]. Surgically induced weight loss is indicated for individuals with a body mass index (BMI) ≥ 40 kg/m^2 or a BMI ≥ 35 kg/m^2 with at least one related comorbidity, such as type 2 diabetes mellitus, hypertension, obstructive sleep apnea syndrome (OSA), and non-alcoholic fatty liver disease (NAFLD) [6].

Despite the growing rate in the number of bariatric surgeries performed each year, the demand is greater than the capacity in several countries, with waiting times of up to 5 years [7–10]. Delaying bariatric surgery was associated with a 3-fold mortality increase and appears to be a more expensive strategy than prompt surgery from the Brazilian public health system perspective [8, 11]. In a modeling study with a 20-year time horizon, waiting 7 years for the procedure compared to performing surgery immediately was the most expensive and least effective strategy [8].

There are no current criteria to establish priority for bariatric surgery candidates in the Brazilian public health system and the waiting time regime adopts a first-in-first-out queue rule. Few scoring systems have been developed, mostly assessing early postoperative mortality predictors or long-term mortality predictors including individuals with overweight and obesity that have not undergone bariatric surgery [12–15].

Considering that bariatric surgery is an elective procedure but with a significant impact on morbidity and mortality, the identification of patients who would obtain the greatest benefits is essential in order to organize the access to surgery. The aim of this study is to identify preoperative predictors of postoperative success, here defined as the sum of five outcome variables, four assessed at baseline and 1 year after the surgery, and one outcome assessed only after the surgery (all-cause mortality). We developed and validated a statistical model based exclusively on patients' preoperative characteristics that allows predicting the success after bariatric surgery and prioritizing patients with the best indication for the procedure.

Materials and Methods

Setting and Study Population

This is a retrospective cohort study including all patients who have undergone bariatric surgery from January 2010 to December 2017 at a tertiary care teaching public hospital in Porto Alegre, Southern Brazil. Roux-en-Y gastric bypass (RYGB) is the only bariatric technique performed in this hospital. The same surgical team performed all surgeries. This study was approved by the local Ethics Committee (2018-0088) and informed consent was not required to conduct this secondary data analysis. Brazil has a publicly funded universal health care system and the hospital is a reference for all medical care at State level (approximately 11.3 million people). Data were selected from hospital's records at the time patients conducted initial exams to be considered eligible for bariatric surgery up to 1 year after the surgery. This study followed the recommendations of the Transparent Reporting of a Multivariable Prediction Model for Individual Prognosis Or Diagnosis (TRIPOD) [16].

Measures and Outcomes

Success of the surgery was defined as the sum of the following five outcome variables, detailed in Table 2 and in the Supplemental Material: (R1) excess weight loss using a BMI of 25 kg/m^2 as a reference for ideal body weight [17], (R2) use of continuous positive airway pressure (CPAP) or bilevel positive airway pressure (BiPAP) as a treatment for OSA, (R3) daily use of antidiabetics (including insulin), (R4) daily use of antihypertensive medication, and (R5) all-cause mortality. Follow-up measures were obtained from patients' scheduled appointments. The choice of the five variables for our composite clinical success score relies on well-reported outcomes after bariatric surgery. In addition to weight loss, the surgery is associated with lower all-cause mortality [18], improvement or remission of type 2 diabetes mellitus [4, 19], hypertension [20, 21], and OSA [22], here assessed by the reduction of the total number of antidiabetic and antihypertensive drugs and CPAP/BiPAP discharge 1 year postoperative, respectively.

Although success outcome variables R1 to R4 were measured at baseline and 1 year after the surgery, data on the following predictors were only assessed at baseline: BMI (kg/m^2), initial excess weight in kg (based on a BMI of 25 kg/m^2), age, gender, marital status, skin color, educational level, waiting time for surgery (since being eligible) in months, self-reported alcoholism and smoking status, hypertension [23], type 2 diabetes mellitus [24], hypercholesterolemia [25], OSA syndrome defined according to the preoperative polysomnography test and/or CPAP or BiPAP use [26], NAFLD defined by the liver biopsy (routinely performed at the same surgical time or by preoperative abdominal ultrasound) [27, 28], history of cardiovascular disease, gastroesophageal reflux and osteoarthritis defined by medical report, major depressive disorder defined by psychiatric report, the amount of daily

antidiabetic, antihypertensive and lipid-lowering drugs, and laboratory data: fasting glucose (mg/dL), total cholesterol (mg/dL), HDL-cholesterol (mg/dL), LDL-cholesterol (mg/dL), triglycerides (mg/dL), and creatinine (mg/dL).

Statistical Analysis

Patient records with missing information on clinical variables were pre-treated using the k-nearest-neighbor (KNN) imputation method from Matlab. An optimal scaling technique from IBM SPSS Statistics, version 18, was used for recoding all numerical, nominal, and categorical variables. We ran a cross-validation leave-one-out model of the partial least squares (PLS) regression using Matlab's iToolbox to compare the imputed ($n = 461$) and the original dataset without missing data ($n = 277$) to predict success including all preoperative predictors.

We performed a 90/10 split of the dataset in train and test sets using the Kennard-Stone technique. Next, we ran a leave-one-out cross-validation procedure on the train set and the best PLS model was chosen based on goodness-of-fit criteria. The best model is then applied to the test set and the final root mean square error (RMSE) measure was determined. A multiple linear regression (MLR) model was performed with stepwise variable selection using the success index as dependent variable and the same predictors tested in the PLS regression, all measured at baseline. The MLR analysis allowed determining the significance of predictors, which is not available from the PLS model.

Additionally, baseline and 1-year post-RYGB characteristics were compared using Student's paired t test or McNemar test and p values (two-tailed) of < 0.05 were considered significant. Quantitative data were shown as mean and standard deviation (SD) or median and interquartile range. Spearman or Pearson correlation analyses were performed on all laboratory data using the difference score from baseline to one-year post-RYGB.

Results

The complete dataset included 461 patients, mostly female (84.6%), white (89.4%), with a mean age of 42.3 ± 10.8 years. The sample consisted mostly of married/cohabiting (47.1%) and single (43.8%) subjects, with a small proportion of divorced (6.7%) and widowed (2.4%) individuals. Most patients had middle school education or less (48.4%), 39.1% had started or completed high school, and 12.5% had started or achieved a graduate degree. Preoperative BMI ranged from 35.0 to 89.2 kg/m^2 with a median excess weight of 61.4 (48.5–77.5) kg. Self-reported mean duration of obesity (defined as a BMI ≥ 30 kg/m^2) was 18.7 ± 9.6 years. Median waiting time for surgery was 30 months [21–41].

Excess weight loss 1 year postoperative was 68.6 ± 17.3%. Table 1 presents the baseline and 1-year post-RYGB clinical and laboratory characteristics. Mortality records sometimes went beyond the 1-year follow-up, but all-cause mortality was low ($n = 17$); of those, eight deaths were related to obesity or surgery complications (sepsis, bronchospasm, hypovolemic shock, and respiratory failure).

Table 2 presents the outcome variables and success index after bariatric surgery. The PLS regression for the data with missing values and the imputed dataset indicated a good fit of the later based on mean absolute percent error (MAPE—a robust to outliers, relative measure of error that compares the model's predictions fit to the corresponding outputs based on the absolute value of the residuals) of 0.112, compared to 0.114 with missing, and root mean square error (RMSE—measure of how much the results are affected by the residuals based on the square root of their absolute value) of 0.471, compared to 0.408 with missing. All subsequent analyses were performed on the imputed dataset.

PLS and MLR models were adjusted to the imputed dataset, considering all-cause mortality (models considering only deaths due to obesity or surgery complications resulted very similar and are not shown here). In Table 3, we present models' statistics and results; only predictors displaying absolute PLS loads greater than 0.3 and/or MLR significance 0.05 or smaller are included. We identified a trend association between the predictive success model and the improvement in metabolic parameters such as fasting blood glucose ($r = -0.166$; $p < .001$), HDL-cholesterol ($r = 0.107$; $p = .002$), and triglycerides ($r = -0.139$; $p = .003$).

Table 4 presents the sample of patients divided in three similar sized groups after organized in ascending order according to a composite indicator that added the patient's success index value and four variables indicating the presence of four comorbidities, with binary outcomes (1 = presence; 0 = absence).

Discussion

Eligibility criteria for bariatric surgery have been exclusively based on BMI since 1991 [6]. Despite overall mortality and most specific causes of death appear to be proportional to BMI increase [29], this approach has been criticized for more than a decade [30]. There are only a few scoring systems available in the literature, which assessed mostly predictors of mortality or complications related to the surgery [12–15, 31, 32]. Some of those scores evaluated individuals with overweight and obesity that have not undergone bariatric surgical procedures. More recently, experts from the Diabetes Surgery Summit consensus series developed a guidance for prioritization of bariatric and metabolic surgeries since most elective

Table 1 Subjects' characteristics at baseline and 12 months after Roux-en-Y gastric bypass

Characteristics	Baseline	12 months	p value
Clinical characteristics			
Body mass index, kg/m^2	49.7 ± 8.7	33.4 ± 6.3	< .001
Current alcohol drinker	3 (0.7%)	5 (1.1%)	.261
Former alcohol drinker	20 (4.3%)	–	–
Current smoker	19 (4.1%)	16 (3.5%)	.782
Former smoker	125 (27.1%)	–	–
Systolic blood pressure (mmHg)	136.5 ± 16.4	119.4 ± 16.0	< .001
Diastolic blood pressure (mmHg)	85.9 ± 12.2	75.7 ± 11.3	< .001
Type 2 diabetes mellitus	142 (30.8%)	33 (7.2%)	< .001
Hypertension	324 (70.3%)	164 (35.6%)	< .001
Hypercholesterolemia	216 (46.9%)	62 (13.4%)	< .001
Obstructive sleep apnea syndrome (OSA)	126 (27.3%)	NA	–
Mild OSA	44 (34.9%)	NA	–
Moderate OSA	29 (23%)	NA	–
Severe OSA	53 (42.1%)	NA	–
CPAP or BiPAP use	89 (19.3%)	48 (10.4%)	< .001
CPAP or BiPAP use time (months)	9.4 (6–15.9)	–	–
Non-alcoholic fatty liver disease*	308 (74.8%)	NA	–
Hepatic steatosis	204 (66.2%)	NA	–
Steatohepatitis	104 (33.8%)	NA	–
Gastroesophageal reflux	44 (9.5%)	NA	–
Major depressive disorder	132 (28.6%)	NA	–
History of cardiovascular disease**	31 (6.8%)	NA	–
Osteoarthritis	84 (18.3%)	NA	–
Medication use			
Oral antidiabetic drugs	131 (28.4%)	31 (6.7%)	< .001
No. of daily oral antidiabetic drugs			
1	82 (62.6%)	24 (77.4%)	
2	41 (31.3%)	7 (22.6%)	
≥3	8 (6.1%)	0 (0%)	
Insulin use	21 (14.8%)	2 (6%)	.002
Antihypertensive drugs	314 (68.1%)	145 (31.5%)	< .001
No. of daily oral antihypertensive drugs			
1	94 (29.9%)	145 (100%)	
2	130 (41.4%)	0 (0%)	
3	58 (18.5%)	0 (0%)	
≥4	32 (10.2%)	0 (0%)	
Lipid-lowering drugs	89 (19.3%)	43 (9.3%)	< .001
Laboratory assessment			
Fasting blood glucose (mg/dL)	112.5 ± 37.3	86.5 ± 14.7	< .001
Total cholesterol (mg/dL)	186.2 ± 36.3	149.8 ± 30.5	< .001
HDL-cholesterol (mg/dL)	44.7 ± 11.95	49.0 ± 11.9	< .001
LDL-cholesterol (mg/dL)	110.8 ± 32.0	82.3 ± 25.7	< .001
Triglycerides (mg/dL)	154.0 ± 77.9	93.0 ± 47.4	< .001
Creatinine (mg/dL)	0.73 ± 0.23	0.66 ± 0.18	< .001

*84.4% was defined by liver biopsy and 15.6% was defined by abdominal ultrasound

**Coronary arterial disease, ischemic heart disease, stroke, heart failure, and cor pulmonale

Data are presented as mean ± SD, median (interquartile range) or proportion n (%). *p value* significance level (two-tailed) for comparison using Student's paired *t* test or McNemar test, *NA* data not available, *BiPAP* bilevel positive airway pressure, *CPAP* continuous positive airway pressure

procedures have been postponed during the coronavirus disease 2019 (COVID-19) pandemic. It is proposed to prioritize bariatric surgery for patients at increased risk for morbidity and mortality according to coexisting comorbidities, i.e., type 2 diabetes mellitus, non-alcoholic steatohepatitis, hypertension, severe OSA, severe obesity hypoventilation syndrome, heart failure, and chronic kidney disease. Noteworthy, the selection of patients by BMI was not considered to be the most

appropriate. Despite the important discussion and the novelty raised by the authors this guidance is a personal view based on expert opinion [33].

To our knowledge, this is the first study that developed and validated a robust statistical model to predict success after a bariatric surgery using a composite indicator based exclusively on preoperative characteristics in a sample of patients who have undergone bariatric surgery.

Table 2 Outcome variables and success index after bariatric surgery

Outcome variable	Scale	Mean (SD)
R1—excess weight loss	Between 0 and 1	0.68 (0.16)
R2—required use of CPAP/BiPAP	Binary (0 or 1)	0.10 (0.30)
R3—number of antidiabetic drugs*	Between 0 and 1	0.77 (0.18)
R4—number of antihypertensive drugs	Between 0 and 1	0.65 (0.37)
R5—all-cause mortality	Binary (0 or 1)	0.98 (0.13)
Success index (sum of responses)	Between 0 and 5	3.19 (0.58)

R1: Excess weight loss was calculated using a BMI of 25 kg/m^2 as a reference. The gradient in BMI (ΔBMI) was used to assess variable (R1): ΔBMI = (BSBMI − ASBMI)/(BSBMI − 25)

R2: Value 1 was assigned to subjects who stopped using CPAP or BiPAP 1 year after RYGB; value 0 was assigned to those who did not require CPAP or BiPAP before surgery and to those who used it and continued using 1 year after surgery

R3: 1—ratio between the daily number of prescribed antidiabetics used before and 1 year after surgery. Subjects who did not require antidiabetics at baseline and remained without medication 1 year postoperatively were given value 0.75

R4: 1—ratio between the daily number of prescribed antihypertensive drugs used before and 1 year after surgery. Subjects who did not require antihypertensive medication at baseline and remained without medication 1 year postoperatively were given value 0.75

R5: Value 1 was assigned to subjects who did not die, and 0, otherwise

ASBMI post-surgery BMI, *BiPAP* bilevel positive airway pressure, *BMI* body mass index, *BSBMI* pre-surgery BMI, *CPAP* continuous positive airway pressure. *Oral antidiabetic drugs and/or insulin.

We found that the patients with a greater likelihood of a successful surgical outcome are younger, presenting preoperative NAFLD and OSA, more years of preoperative CPAP/BiPAP use, negative history of cardiovascular disease, and lower number of daily antihypertensive drugs. As

Table 3 Partial least squares loadings, multiple linear regression coefficients, and goodness-of-fit statistics of preoperative predictors of success after bariatric surgery

Preoperative predictor	β	*p* value	PLS load
Age, years	− .22	.0002	.3775
Non-alcoholic fatty liver disease	.11	.0266	.2242
CPAP/BiPAP use time, years	.14	.0418	.3929
Obstructive sleep apnea syndrome	.18	.0074	.4058
Negative history of CVD	.11	.0267	.3140
Number of antihypertensive drugs	− .13	.0746	.3912

PLS: 1 principal component retained, MAPE = .1121, RMSE = .4705
MLR: R^2 = .182, RMSE = .544

Dependent variable: success index. Model considering all-cause mortality. *Abbreviations: BiPAP* bilevel positive airway pressure, *CPAP* continuous positive airway pressure, *CVD* cardiovascular diseases, *MAPE* mean absolute percent error, *MLR* multiple linear regression, *PLS* partial least squares, *RMSE* root mean squared error

opposed to the conventional wisdom, a higher preoperative BMI did not predict the postoperative success index. The rationale could be that once a specific degree of obesity is established, the BMI becomes no longer an important predictor, as our sample was composed by 92% of individuals with preoperative BMI higher than 40 kg/m^2. This result is in line with previous evidence from larger samples assessing mortality predictors [12, 13]. We found a low prevalence of preoperative cardiovascular disease (6.8%) and this could explain the reason why negative history of cardiovascular disease was a predictor of greater success after surgery. Although bariatric surgery is associated to reduced cardiovascular risk, the prevalence of patients with a preoperative history is remarkably low [34, 35]. In the large Swedish Obese Subjects (SOS) study, only 1.5% candidates for bariatric surgery had a history of cardiovascular disease [35].

Padwal et al. [12] assessed predictors of 10-year all-cause mortality in a sample of 15,394 subjects eligible for bariatric surgery and identified a 4-variable clinical prediction rule that included higher age, male sex, type 2 diabetes mellitus, and current smoking. Even after sensitivity analysis, BMI was not an important mortality predictor. Another study evaluated the ability of the Edmonton Obesity Staging System (EOSS) to predict mortality among 7967 adults with overweight and obesity; of those, 1106 were candidates for bariatric surgery [13]. The EOSS is a 5-point ordinal classification system that considers comorbidities and functional limitations and/or impairment of well-being related to obesity. Scores of 2 (hazard ratio [HR] 1.57; 95% CI 1.16 to 2.13) and 3 (HR 2.69; 95% CI 1.98–3.67) were associated with an increased mortality when compared to scores of 0 or 1 in both the overall population and the cohort eligible for bariatric surgery, independently of BMI. Patients' preferences were also considered regarding prioritization for bariatric surgery [32, 36]. A Canadian study assessed the patients' perspectives and found clinical severity and functional impairments related to obesity as the main factors that should be considered in the prioritizing setting [36]. Despite the strengths of each approach, the first concern that emerges is that those scores addressed a population that has not undergone bariatric surgery. Secondly, the only outcome investigated in both scores mentioned above was mortality which requires a long-term follow-up. Thirdly, in order to prioritize the access to surgery, the assessment of functional status of all eligible patients waiting for the surgical treatment might be a challenge in clinical practice.

The metabolic effects of bariatric surgery on comorbidities extend beyond the excess weight loss and impacts on type 2 diabetes mellitus, dyslipidemia, and hypertension remission, improving the OSA and NAFLD severity and reducing the cardiovascular risk and overall mortality. Therefore, we developed and validated a composite score that comprises the sum of five outcome variables to best predict success in bariatric surgery according to the

Table 4 Patients grouped in ascending order according to a composite indicator that considers a success index after bariatric surgery and the prevalence of preoperative comorbidities

Success	N	Avg success index	Composite indicator	OSA	T2DM	Hypertension	BMI > 40
Low	154	2.50	2.50; 4.63	3	7	55	132
Medium	153	3.26	4.63; 5.66	27	36	127	142
High	154	3.75	5.66; 8.70	96	99	142	150
Total	461			126	142	332	424

Avg average, *BMI* body mass index, *OSA* obstructive sleep apnea syndrome, *T2DM* type 2 diabetes mellitus

literature [4, 5, 19, 20, 22, 37–39]. Besides the excess weight loss and all-cause mortality, we assessed the reduction of the total number of antidiabetic and antihypertensive drugs and the required use of CPAP/BiPAP at 12 months postoperative compared to the baseline as a *proxy* to type 2 diabetes mellitus, hypertension, and OSA improvement, respectively.

A systematic review including six cohort studies showed long-term (range 5 to 15 years) increased type 2 diabetes mellitus remission (relative risk = 5.90; 95% CI 3.75 to 9.28) after bariatric surgery as compared to non-surgical treatment [4]. We found 76% of type 2 diabetes mellitus remission without pharmacological therapy 12 months after surgery. Panunzi et al. [19] found 64% of type 2 diabetes mellitus remission 2 years after bariatric surgery.

Regarding systemic arterial hypertension, a randomized clinical trial assessed the impact of RYGB plus medical therapy versus medical therapy alone and found that patients in the surgical group were six times more likely to reduce ≥ 30% of total number of antihypertensive drugs 1 year after the surgery, whereas 51% presented hypertension remission [20]. In our sample, 54% of hypertensive patients were free of antihypertensive medications at 12 months and 49.4% showed hypertension remission.

Obesity is recognized as a major risk for OSA and its prevalence is higher than 60% in the bariatric surgery population [40, 41]. However, in this study, we found a lower prevalence of OSA (27%). In our center, only patients who screen positive for STOP-BANG questionnaire are referred to polysomnography test and it is likely that OSA asymptomatic patients have undergone the surgery [42, 43]. Thus, we assessed the required use of CPAP/BiPAP prior and after surgery as a *proxy* to OSA improvement in the predictive model of success.

This study has inherent limitations related to its observational design and missing data. Moreover, the generalizability of this study is limited because only RYGB is offered in our institution. The strengths are the novelty of data mining and the robust statistical methodology which was succeed on its purpose. The PLS model displayed a MAPE of 0.1121 in the test portion of the dataset, leading to accurate predictions of postoperative outcomes. The composite indicator presented

on Table 4 clearly shows that the high-success level comprises patients with greater number of comorbidities, whereas class III obesity was homogeneously distributed into the three success groups.

Hence, our clinical composite indicator to predict success based on preoperative characteristics allows prioritizing patients with best indication for bariatric surgery and could be incorporated in the public health system as a support tool in the decision-making process, possibly leading to lower healthcare costs and mortality.

Conclusion

This study developed and validated an accurate predictive model that comprises the sum of five outcome variables to predict success in bariatric surgery based exclusively on patients' preoperative characteristics. Preoperative predictors of success after bariatric surgery included lower age, presence of NAFLD and OSA, more years of CPAP/BiPAP use, negative history of cardiovascular disease, and lower number of antihypertensive drugs. The success index may help in prioritizing eligible patients waiting for bariatric surgery with the highest indication for the procedure and should be considered for incorporation in the public health system as a support tool in the decision-making process.

Compliance with Ethical Standards

institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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