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ORIGINAL CONTRIBUTIONS

Weight Loss and Changes in Adipose Tissue and Skeletal Muscle Volume after Laparoscopic Sleeve Gastrectomy and Roux-en-Y Gastric Bypass: a Prospective Study with 12-Month Follow-Up

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Abstract

Background This study aimed to evaluate changes in body tissue composition with obesity surgery regarding visceral fat, subcutaneous fat, and skeletal muscle.

Design Prospective non-randomized single-center cohort study

Methods Whole-body magnetic resonance imaging (MRI) measured volumes of subcutaneous adipose tissue (SAT), visceral adipose tissue (VAT), and skeletal muscle (SM) in 31 patients with laparoscopic sleeve gastrectomy (LSG, 20) or Roux-en-Y gastric bypass (RYGB, 11) preoperatively, at three- and 12-months follow-up.

Results Body mass index (BMI) went down from 45.2 ± 6.5 preoperatively to 37.2 ± 5.6 ($p < 0.001$) at three months and 32.2 ± 5.3 kg/m^2 ($p < 0.001$) at 12 months. SAT went down from 55.0 ± 14.0 L (liter) to 42.2 ± 13.3 L ($p < 0.001$) at three months and 31.7 ± 10.5 L ($p < 0.001$) at 12 months (− 42.3%). VAT went down from 6.5 ± 2.3 to 4.5 ± 1.7 ($p < 0.001$) at three months and 3.1 ± 1.7 L ($p < 0.001$) at 12 months (− 52.3%). SM went down from 22.7 ± 4.8 to 20.4 ± 3.6 ($p = 0.008$) at three months and remained 20.2 ± 4.6 L at 12 months ($p = 0.17$ relative three-month; $p = 0.04$ relative preop, − 11.1%). Relative loss was higher for VAT than that for SAT (52.3 ± 18.2% vs. 42.3 ± 13.8%; $p = 0.03$). At 12 months, there was no difference between LSG and RYGB for relative changes in BMI or body tissue composition.

Conclusion Postoperatively, there was higher net loss of SAT but higher relative loss of VAT with weight loss. SM was lost only during the first three months. MRI provides accurate evaluation of surgeries' effect on individual patients' tissue composition. This can benefit risk assessment for related cardiovascular and metabolic health but cost-related factors will likely reserve the used methods for research.

Keywords Obesity surgery · Roux-en-Y gastric bypass · Laparoscopic sleeve gastrectomy · Weight loss · Fat volume · Adipose tissue · Muscle volume · MRI · Image processing · Segmentation

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Abbreviations

BMI	Body mass index
LSG	Laparoscopic sleeve gastrectomy
RYGB	Roux-en-Y gastric bypass
SAT	Subcutaneous adipose tissue
SD	Standard deviation
SM	Skeletal muscle
VAT	Visceral adipose tissue

Introduction

Obesity is a significant healthcare problem in the developed world [1]. The percentage of the population with a body mass index (BMI) of 30 or greater has trended steadily upwards over the past decades and will likely continue to increase [2, 3]. Laparoscopic sleeve gastrectomy (LSG) and Roux-en-Y gastric bypass (RYGB) have become standard of care for obese patients requiring long-term weight loss [4, 5]. The effectiveness of these procedures for weight loss has been studied and documented, often with follow-ups after multiple years, and have proven to be effective from the perspective of achieving lasting reduction of BMI and bodyweight [6], but also for improvement of obesity-related comorbidities and quality of life [5, 7–10]. Some studies have been conducted evaluating the clinical markers subcutaneous adipose tissue (SAT)% and glycated hemoglobin (HbA_{1c}) [11] concentration with regard to the predicting effectiveness of obesity surgery to induce remission of type 2 diabetes mellitus in patients with obesity [12, 13]. It has also been shown that the percentage of visceral adipose tissue (VAT) is a significant clinical marker for long-term patient health and is highly correlated with metabolic syndrome [13] and high-risk vascular diseases [14], such as atherosclerosis and coronary artery disease. Measuring the effect of obesity surgery on the tissue composition of patients is therefore a desirable parameter for assessing the individual post-surgical outcome and stratifying risk and risk-reduction mostly for cardiovascular and metabolic health.

Current studies investigating changes in body composition after surgery commonly use dual-energy X-ray absorptiometry and single-slice MRI data for assessment [15–18]. However, studies assessing the total (whole-body) change in tissue composition, especially comparing skeletal muscle (SM) to types of adipose tissue, have rarely been conducted, and rarely over a time-frame of more than six months. This is where we believe the present study can contribute, as changes not only in BMI but also in relative SM-to-adipose ratio are likely to play a role in long-term improvement of patient health. The aim of this study therefore is to assess the potential of monitoring changes in SAT, VAT, and SM over time with whole-body MRI.

The present study is part of a prospective longitudinal cohort study which begun in 2011 at the Department of General, Visceral, and Transplantation Surgery at Heidelberg University Hospital evaluating Postoperative Constitutional Changes in Obesity (POCCO). The main goal of the POCCO study was the evaluation of changes in gastric size after obesity surgery in patients with a preoperative BMI > 35 kg/m^2, as a recent study by Evers et al. [19] showed a direct correlation between residual postoperative stomach volume and sustained weight loss. The present study is a result of the evaluation of the whole-body MRI data from the POCCO patients. Gastric size and long-term weight loss as well as weight regain will be evaluated with a longer follow-up separately from the present manuscript.

The hypothesis of the present study as an adjunct to the original POCCO study is that obesity surgery leads to significant change in body composition and influences the tissue components of VAT, SAT, and SM in different ways. Thus, the resulting null hypothesis should be formulated as "Evaluation one year after obesity surgery yields no significant ($\alpha < 0.05$) change in body composition."

Methods

Patients

Criteria for inclusion into the study were a BMI between 35 and 60 kg/m^2, as well as a clear indication for obesity surgery according to German S3 guidelines as evaluated in a multidisciplinary setting in an obesity center. A psychosomatic and endocrine profile was done on all patients to ensure no contraindications to surgery were present. Criteria for exclusion were inability to undergo an MRI for any reason, e.g., metal implants, claustrophobia, pacemaker, and patient size exceeding MRI capacity. Further criteria for exclusion were pregnancy and inability to consent for language or other reasons. MRI data of 31 individuals in the POCCO study was collected between July 2012 and March 2017. MRI scans were performed pre-surgery, at a three-month follow-up, and at a 12-month follow-up. Patients were additionally screened for the following comorbidities commonly associated with metabolic syndrome: type 2 diabetes mellitus, arterial hypertension, sleep apnea, and gastroesophageal reflux (GERD). Results of the screening are presented below. In regard to the analysis of the comorbidities, the null hypothesis would be that there is no change in prevalence of comorbidities when comparing pre-surgical data to that after 12 months. As these are binary variables (disease present versus disease absent), chi-squared analysis was used.

Postoperative Assessment

Standard postoperative multivitamin dosing was two tablets per day. Patients were followed-up on their diet at the measurement intervals. Any reported problems were assessed to exclude surgical complications such as stenosis, adhesions, or hernia. Assessment and consultation with a dietician were arranged in individual cases.

Magnetic Resonance Imaging

The MRI data was collected at the Department of Diagnostic and Interventional Radiology of Heidelberg University Hospital. T1-weighted axial images (T1 Dixon vibe, 3-mm slice thickness, 1.302 × 1.302 mm matrix) covering the neck to the ankles were obtained using a "MAGNETOM Aera" 1.5 Tesla MRI scanner with a 70-cm wide bore design (Siemens Healthcare GmBH, Erlangen, Germany). A two-point Dixon protocol with gradient echo technique using parallel acquisition mode was chosen, which allows for acquisition of high-resolution three-dimensional volumes. Participants were measured in a supine position with the arms at their sides. Due to the limited field-of-view of the MRI device, the arms are often found partly or even completely outside of the image. To ensure a consistent analytical approach to body volume measurements of all participants, the arms were removed at the armpits during data processing. Classical MRI contraindications were used with no need for administration of contrast agent. MR software, hardware, and protocol were constant during the study time points to reduce interscan-variability.

Medical Imaging Interaction Toolkit

The software which was used for this study is based on the Medical Imaging Interaction Toolkit (MITK) [18]. MITK is an open source image processing application currently in use for research at the medical faculty of the University of Heidelberg. It was developed based on the open source tools Visualization Toolkit (VTK) (Kitware Inc., Clifton Park, NY, USA), Insight Segmentation and Registration Toolkit (ITK) (United States National Library of Medicine, Bethesda, MD, USA; Kitware Inc., Clifton Park, NY, USA; et al.), and Qt Bibliothek (The Qt Company, Espoo, Finland). It has been in use since 2002 and can be utilized for visualization of medical images, as well as image processing and segmentation. The software used for the segmentation and quantification of adipose and skeletal muscle tissue is described in detail elsewhere [19] (Figs. 1, 2, 3, and 4).

Whole-Body Segmentation

However, due to the extreme body volumes of the patients, MRI coils which maximize the signal-to-noise ratio could not be used for the acquisition and resulted in a reduced image quality. The software for automatic segmentation of the adipose and skeletal muscle tissue did not work properly for all slices in the whole-body datasets, in particular for preoperative data. For this reason, the transverse MRI slices had to be reviewed and corrected manually, using the open source

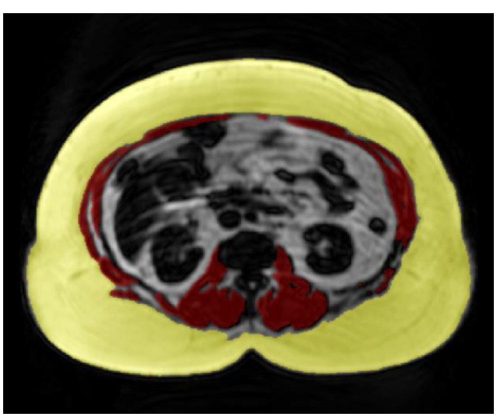

Fig. 1 Transverse MRI segmentation, marked for SAT (yellow) and SM (brown)

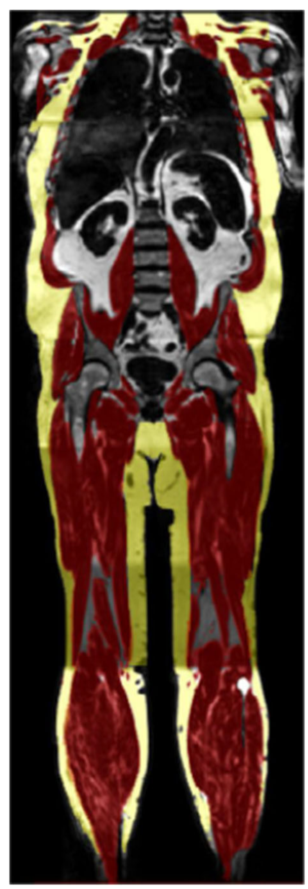

Fig. 2 Whole-body MRI segmentation in the coronary plane, marked for SAT (yellow) and SM (brown)

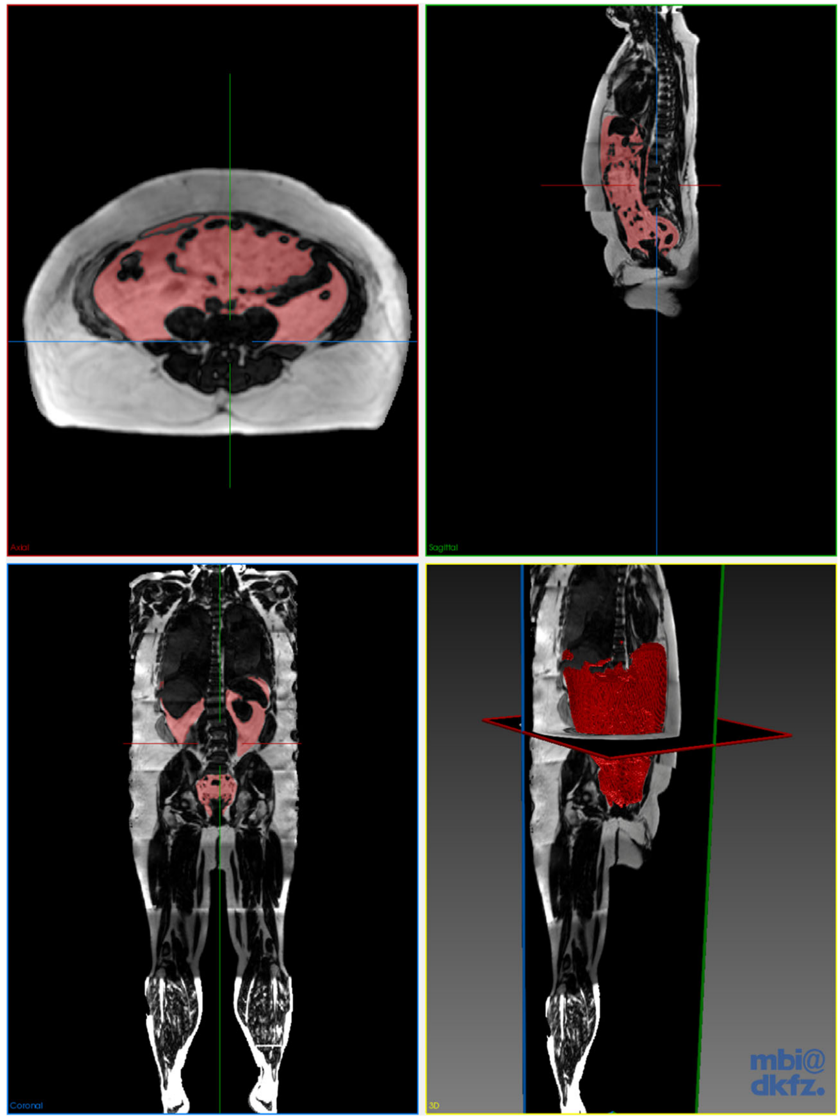

Fig. 3 3D-reconstruction of visceral fat volume using the MITK software

segmentation module of MITK [20]. The segments were marked and labeled for SAT, VAT, and SM on each transverse MRI slice. The labeled tissue was then merged across all slices to acquire the total body volume of each tissue of interest.

Statistics

The results of the segmentations were collected in a Microsoft Excel 2016 worksheet; the statistical analysis was carried out with IBM SPSS Statistics 24. Values across the study population are presented as mean and standard deviation (SD) where appropriate. The collected data was then subjected to the Kolmogorov-Smirnov test to determine the presence or absence of a normal distribution in the patient population, as well as Levene's test to determine any homogeneity of variance. For analysis of patient data across time, the Wilcoxon signed-rank test was used in comparing related samples. Statistical significance for all tests was set at $p \leq 0.05$.

Ethical Approval

The study was approved by the ethics committee of Heidelberg University prior to the beginning of the study (24 October 2011, S-450/2011). All participants were given a comprehensive explanation of the surgical procedures involved, including follow-up and possible complications, by a trained medical professional. All participants were also briefed on the nature of the study and gave written permission for their data to be used.

Results

Patient Characteristics

The included patients underwent obesity surgery at Heidelberg University Hospital (18 women and 13 men).

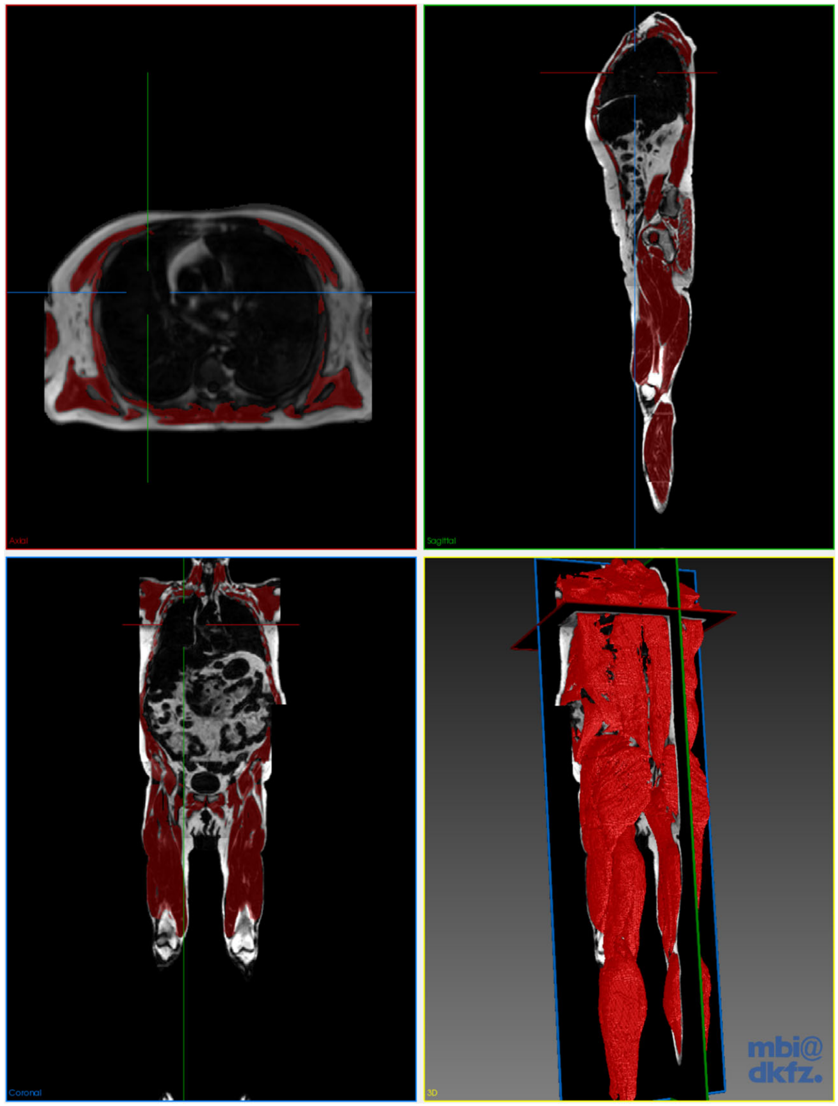

Fig. 4 3D-reconstruction of skeletal muscle volume using the MITK software

Five women and six men received RYGB, and 13 women and seven men received LSG. Patients were 46.4 ± 9.7 years old and 173.6 ± 9.8 cm tall, and BMI at baseline was 45.2 ± 6.5 (Table 2). At 12 months, one patient was lost to follow-up, resulting in a 3.2% dropout rate. Only patients who completed the 12-month follow-up were included in the analysis. Comorbidities pre- and post-surgery are summarized in Table 1, both in summary and split by surgical procedure.

Table 1 Patient comorbidities

	LSG ($n = 20$)			RYGB ($n = 10$)			Total ($n = 30$)		
	Pre	12 months	p value	Pre	12 months	p value	Pre	12 months	p value
Type 2 diabetes	10	4	*0.047*	6	1	*0.019*	16	5	*0.003*
Hypertension	13	8	0.113	6	2	0.068	19	10	*0.020*
Sleep apnea	4	1	0.151	4	0	*0.025*	8	1	*0.011*
GERD	2	2	1.000	1	1	1.000	3	3	1.000
Sum comorbidities	29	15	*0.013*	17	4	*0.001*	46	19	*< 0.001*

Patient comorbidities at preop and 12 months postop, sorted by surgical procedure. Significant p values are italicized

Table 2 Summary of measurements

Total study ($N = 30$)

	Initial values	3 months			12 months		
	Measured	Measured	Changes	*p* value	Measured	Changes	*p* value
BMI	45.6 ± 6.3	37.2 ± 5.6	8.1 ± 3.1	*< 0.001*	32.2 ± 5.3	13.1 ± 4.8	*< 0.001*
Weight [kg]	137.1 ± 19.2	112.4 ± 17.4	24.0 ± 8.1	*< 0.001*	97.2 ± 16.5	39.2 ± 13.6	*< 0.001*
%TWL [%]			17.5 ± 5.4			28.4 ± 8.3	
%EWL [%]			40.0 ± 11.8			65.0 ± 18.8	
SM [L]	22.5 ± 4.7	20.4 ± 3.6	2.2 ± 2.9	*0.008*	20.2 ± 4.6	2.3 ± 3.4	*0.001*
[%]			8.6 ± 11.7			9.3 ± 16.8	
SAT [L]	55.9 ± 13.3	42.2 ± 13.3	12.8 ± 6.1	*< 0.001*	31.7 ± 10.5	24.2 ± 9.6	*< 0.001*
[%]			23.5 ± 11.1			43.0 ± 13.4	
VAT [L]	6.5 ± 2.4	4.5 ± 1.7	1.9 ± 1.3	*< 0.001*	3.1 ± 1.7	3.4 ± 1.7	*< 0.001*
[%]			28.3 ± 13.8			52.4 ± 18.2	

Total study average of body changes over time. Tissue changes given in absolute values [L] and relative to preop weight [%]. *%TWL*, percent total weight lost; *%EWL*, percent excess weight lost

Changes over Time

Over the 12-month period, all patients experienced loss of volume in SM, SAT, and VAT. All patients also lost weight and had a reduced BMI. Changes to all parameters, including weight/BMI, were higher in absolute values over the first three months than over the following nine months (Table 2). In all patients, a decrease of both SAT/SM and VAT/SM ratios could be observed over the 12-month period (Table 2), meaning that a greater percentage of SAT and VAT was lost compared with SM. Over the observed period, a greater percentage of total VAT was lost compared with SAT (Table 2). Also, a decrease in muscle volume was observed over the initial three months; however, the follow-up at 12 months showed no additional change of SM on average, with some patients regaining SM volume compared with the three-month measurement.

Comparison by Gender

Differences in height, weight, BMI, and tissue distribution were observed between men and women. Men, on average, were taller and had more SM and VAT but had a lower BMI than women prior to surgery. The post-surgical measurements when analyzed by relative loss of body tissues yielded a significant difference between men and women only in VAT at the three-month mark. All other relative changes (SAT, SM, BMI, excess weight loss) yielded no significant differences. The results are displayed in Table 3.

Comparison of Surgical Procedures

The three- and 12-month outcomes were compared for both procedures by tissue. The patients undergoing LSG had a significantly higher BMI and significantly higher volume of SAT preoperatively while there were no differences in SM and VAT (Table 4). Because of the unequal volume and BMI at the time of surgery, both absolute and relative changes in volume were analyzed. At three months, patients after LSG had a significantly higher absolute reduction in BMI compared with the RYGB patients, but this was not consistent with the relative BMI reduction. RYGB patients lost a greater relative amount of VAT but this was not the case for absolute amount of VAT. Other tissue changes were similar across both groups. At 12 months, no significant absolute or relative differences were found between RYGB and LSG patients (Table 4).

Comorbidities

Patients were evaluated for persistence of comorbidities at 12-months post-surgery, on the same day they received the MRI. The results are displayed in Table 1. Across the study population, prevalence of type 2 diabetes ($p = 0.003$), hypertension ($p = 0.02$), and sleep apnea ($p = 0.011$) was significantly reduced. Type 2 diabetes persisted in five of the 16 patients, resulting in a relative reduction of 68.7% and an absolute reduction in prevalence of 36.6% for the whole patient group. Arterial hypertension persisted in 10 of the 19 patients, resulting in a relative reduction of 47.3% and an absolute reduction in prevalence of 30.0% for the whole

Table 3 Comparison by gender

Initial values	Men ($N = 12$) Mean	Women ($N = 18$) Mean	p value
Height [cm]	182.6 ± 7.2	167.8 ± 6.2	*< 0.001*
Age [years]	45.7 ± 9.2	47.0 ± 10.0	0.61
Weight [kg]	139.3 ± 13.9	134.4 ± 22.0	0.67
BMI	41.9 ± 4.7	47.7 ± 6.6	*0.01*
VAT [L]	8.4 ± 1.8	5.2 ± 1.7	*< 0.001*
SAT [L]	49.6 ± 12.1	58.9 ± 14.0	0.06
SM [L]	26.6 ± 3.6	19.9 ± 3.3	*< 0.001*
Loss (3 months)			
BMI	7.7 ± 11.7	8.3 ± 15.2	0.62
Weight [kg]	25.3 ± 6.9	23.1 ± 9.0	0.44
%TWL [%]	18.3 ± 5.2	17.1 ± 5.7	0.55
%EWL [%]	47.5 ± 16.1	37.2 ± 11.2	0.06
SM [L]	3.1 ± 3.0	1.8 ± 2.9	0.22
[%]	10.9 ± 11.1	7.4 ± 12.5	0.42
SAT [L]	13.5 ± 5.8	12.3 ± 6.3	0.57
[%]	29.1 ± 13.5	20.5 ± 8.8	0.06
VAT [L]	3.0 ± 1.3	1.2 ± 0.8	*< 0.001*
[%]	35.7 ± 14.0	24.6 ± 14.2	*0.04*
Loss (12 months)			
BMI	11.9 ± 4.0	13.9 ± 5.3	0.25
Weight [kg]	39.3 ± 2.4	39.1 ± 3.5	0.97
%TWL [%]	28.2 ± 8.3	28.8 ± 8.6	0.83
%EWL [%]	73.0 ± 26.5	63.1 ± 19.1	0.26
SM [L]	2.4 ± 2.9	2.2 ± 3.9	0.91
[%]	8.5 ± 11.1	9.9 ± 18.9	0.80
SAT [L]	21.6 ± 6.6	25.9 ± 11.3	0.2
[%]	42.3 ± 11.7	43.4 ± 15.0	0.83
VAT [L]	4.6 ± 1.8	2.6 ± 1.2	*0.002*
[%]	55.5 ± 19.5	50.3 ± 18.0	0.47

Comparison of relative tissue changes by gender. Tissue changes given in absolute values [L] and relative to preop weight [%]. Significant p values are italicized. *%TWL*, percent total weight lost; *%EWL*, percent excess weight lost

Table 4 Comparison by surgery

		RYGB ($N = 10$)		LSG ($N = 20$)		
Initial values		Mean	SD	Mean	SD	p value
BMI		41.2	± 4.4	47.9	± 5.8	*0.003*
Weight [kg]		128.7	± 13.4	141.3	± 20.2	0.06
SM [L]		23.0	± 5.6	22.3	± 4.2	0.72
SAT [L]		48.8	± 10.8	59.4	± 13.0	*0.03*
VAT [L]		6.8	± 3.0	6.3	± 2.0	0.66
Loss (3 months)						
BMI	Absolute	6.7	± 1.6	8.7	± 3.4	*0.04*
Weight [kg]	Absolute	21.1	± 5.8	25.5	± 8.7	0.13
%TWL [%]		16.3	± 3.8	18.1	± 6.2	0.33
%EWL [%]		42.8	± 10.6	38.7	± 12.6	0.35
SM [L]	Absolute	2.4	± 2.7	2.1	± 3.1	0.80
[%]	Relative	9.4	± 21.1	8.2	± 12.7	0.80
SAT [L]	Absolute	13.8	± 5.9	12.3	± 6.0	0.56
[%]	Relative	28.8	± 19.6	20.9	± 9.5	0.11
VAT [L]	Absolute	2.7	± 1.4	1.5	± 1.0	0.06
[%]	Relative	38.0	± 17.3	23.4	± 13.9	*< 0.001*
Loss (12 months)						
BMI	Absolute	11.8	± 3.9	13.7	± 5.0	0.27
Weight [kg]	Absolute	36.5	± 10.7	40.5	± 14.7	0.42
%TWL [%]		28.3	± 8.3	28.4	± 8.7	0.97
%EWL [%]		73.5	± 19.8	60.8	± 17.8	0.11
SM [L]	Absolute	1.4	± 4.0	2.8	± 3.0	0.37
[%]	Relative	4.5	± 18.4	11.7	± 13.6	0.31
SAT [L]	Absolute	22.7	± 9.1	24.9	± 9.8	0.56
[%]	Relative	46.0	± 14.1	41.4	± 12.6	0.42
VAT [L]	Absolute	4.0	± 2.1	3.1	± 1.4	0.24
[%]	Relative	59.9	± 14.1	48.6	± 18.8	0.09

Comparison of patient characteristics by surgical procedure. Tissue changes given in absolute values [L] and relative to preop weight [%]. Significant p values are italicized. *%TWL*, percent total weight lost; *%EWL*, percent excess weight lost

patient group. Sleep apnea persisted in one of the eight patients, resulting in a relative reduction of 87.5% and an absolute reduction in prevalence of 23.3% for the whole patient group. Symptoms persisted at 12 months in all three patients who had previously reported GERD, resulting in no discernible reduction in prevalence in the patient group. When comparing by surgical procedure, it was found that patients who had undergone LSG had significant reduction of the sum of comorbidities ($p = 0.013$) and specific significant reduction in prevalence of type 2 diabetes ($p = 0.047$). Patients who had undergone RYGB had significant reduction of the sum of comorbidities ($p = 0.001$) and specific significant reduction in prevalence of type 2 diabetes ($p = 0.019$) and sleep apnea ($p = 0.025$).

Postoperative Complications

Postoperative complications were recorded prospectively. One patient after RYGB had an insufficiency of the jejunojejunostomy that was successfully treated with laparoscopic revision of the anastomosis one week after primary surgery. One patient had a staple line leak after LSG that was successfully treated with stent placement. No further postoperative complications were recorded.

Discussion

In the present study, changes in body composition were evaluated in 30 patients undergoing obesity surgery with whole-body MRI at the time of operation as well as three- and 12-months follow-up and showed a loss of volume in VAT, SAT, and SM. VAT had the greatest and SM the least relative change while SAT had the highest absolute change. There were no relevant and consistent subgroup differences for gender and type of surgery. In particular, the significantly higher change in VAT and SAT compared with SM preop and after 12 months allows a rejection of the null hypothesis formulated in the "Introduction" section, as a significant change in body composition was found in the study.

Findings in the present study confirm previous work showing that RYGB and LSG are effective methods for weight loss in patients with morbid obesity [4, 6]. The present study further showed that weight loss was mainly due to loss of SAT followed by VAT and that relatively less muscle mass was lost than either type of adipose tissue. While absolute loss was higher in SAT, the relative loss of VAT was higher. Reduction of VAT in particular is of interest for obesity-related problems such as insulin sensitivity [15, 21, 22], non-alcoholic fatty liver disease [9, 23, 24], and cardiovascular disease [25, 26]. The SAT:VAT ratio additionally appears to have clinical significance in chronic inflammatory diseases such as Crohn's. The retention of muscle volume should be emphasized as a potentially important result after obesity surgery to avoid sarcopenia [11, 13–15, 27]. The correlation between obesity and multiple types of cancer has also been discussed [28–33]. In this context, the large absolute reduction in SAT should be emphasized as a desirable outcome of obesity surgery, as it is the largest contributing factor to the actual weight loss, while reduction of VAT seems to be strongly linked to risk of cardiovascular disease. The present study showed a significant reduction in prevalence in type 2 diabetes, hypertension, and sleep apnea across the patient population. It could not show any change in prevalence of GERD. As seen in Table 1, both LSG and RYGB patients showed a significant reduction in comorbidities after 12 months. This shows that obesity surgery does not only achieve the primary goal of weight reduction but can also aid in management of comorbidities associated with metabolic syndrome, if the criteria for surgery are met in the individual patient. These findings are in keeping with previous work by Buchwald et al., showing significant reduction in comorbidities after obesity surgery [34, 35].

When comparing the study population by gender, it was found that men were taller and had a lower BMI on average before surgery. Additionally, the pre-surgery volume of VAT and SM was significantly higher in male patients, but not the volume of SAT. In regard to the weight loss postoperatively, men had higher relative loss of VAT at the three-month follow-up than women. This could be explained in part by the fact that men had a significantly higher initial VAT, and so lost more tissue initially. This additionally explains the significantly greater loss of absolute VAT volume among men. In the 12-month analysis, however, men and women lost an equal relative amount of VAT, SAT, and SM. This is in line with the findings by Xu et al. who found no significant differences when measuring post-obesity surgery outcomes between men and women [36].

When comparing the two surgical procedures used, it was found that patients undergoing LSG had a significantly higher BMI than those undergoing RYGB before surgery. This difference is likely a contributing factor to the higher net loss of BMI in the first three months among patients after LSG compared with RYGB. Despite this initial change, the present study yielded no significant differences between LSG and RYGB in the 12-month assessment of either absolute weight loss or %EWL. At the three-month evaluation, patients who had undergone RYGB surgery had lost significantly more VAT than patients in the LSG group; however, this difference did not persist at 12 months. While the present study may have found no significant difference between the two studied procedures at 12 months, the results at three months should nonetheless be considered a point of interest in possible future studies to compare the procedures. Possible sources for a type II error in this analysis, i.e., finding no significant difference between the surgical procedures when a difference does actually exist, include the difference in initial patient characteristics (different BMI, SAT at operation) and the relatively small sample size.

In the present study, whole-body MRI was an effective method for measuring changes in body composition in morbidly obese patients undergoing obesity surgery. The method yielded additional information for measuring the actual response to therapy when compared with pure BMI and body weight measurements. Measurement of VAT, SAT, SM, and ratios between these values over time can currently only be achieved by imaging methods [16, 17]. While bioelectrical impedance analysis (BIA) may present a possible future alternative in the clinical setting, current studies show that the accuracy of the measurements obtained by BIA can vary, is highly dependent on finding the correct predictive equation, and is influenced by external factors and population epidemiology [37, 38]. In regard to our study population, current studies of BIA have not validated this method for extreme BMI ranges [39]. Furthermore, there is little evidence that BIA can accurately differentiate between subcutaneous and visceral fat at high BMI ranges [39]. As VAT and SAT are strong indicators of long-term therapeutic success and patient health [10, 11, 13–15, 27], monitoring these values could be of significant clinical use, VAT volume in particular being highly correlated with metabolic syndrome and vascular disorders such as coronary artery disease. As these are highly prevalent diseases correlating strongly with increasing obesity [5, 10, 13, 25, 40], we would argue that more precise measurements of tissue composition of patients having undergone obesity surgery are therefore useful for assessing the individual post-surgical outcome and stratifying risk for long-term postoperative metabolic and cardiovascular health. Sarcopenia could be precisely evaluated with the here evaluated method. Furthermore, in cases where patients become frustrated by lack of visible changes after surgery, having more accurate data for discussion could lead to improved postoperative therapy compliance and thus increased therapeutic success [41]. Beyond the uses outlined here, further studies could assess the outcome of non-invasive weight loss therapy by a similar method, and larger-scale studies should evaluate differences between surgical procedures and influence on resolution of comorbidities.

In our study, the MRI data of all patient's arms were removed before analysis. As previously stated, this was done in order to homogenize the patient data and avoid resulting errors in analysis. This results in a removal of between approximately 11.4% (men) and 9.8% (women) of total body mass from the body composition analysis [42]. This is certainly a limitation. However, this should not be seen as compromising to the core hypothesis of the study, as weight loss and changes in body composition tend to affect the entire body. Also, a comparative compositional analysis of the upper arm and thigh in adults by Yamauchi et al. demonstrated similar proportions of SM and SAT in both [43]. It is therefore unlikely in our estimation that the removal of the arms in our analysis would have impacted the highly significant change in body composition after 12 months.

In the short term, large-scale integration of whole-body MRI remains likely unfeasible in clinical routine. In addition to the financial cost of acquiring at least three full scans per patient, the amount of time required to integrate these scans into clinical routine is beyond the scope of most radiology departments. Furthermore, the time and staff required for manual segmentation of the MRI scans are limiting factors, as automatic segmentation software is currently not accurate enough for clinical practice. In the present study in particular, due to the unusual volume distribution, the automatic segmentation software integrated in MITK resulted in too many artifacts to be usable without manual correction. The first step in finding a solution to integrating MRI data into a therapy plan would be assessing whether a reduced selection of segments, or possibly single-slice MRI, could provide reasonable accuracy when assessing SM, SAT, and VAT. Previous studies, such as a 2015 study from Schweitzer et al. and the Framingham Heart Study, looked at the possibility of estimating these tissue volumes from single-slice data [44, 45]. In healthy individuals, L3/L4 was found to be the most accurate segment, however could not be used to accurately measure changes in body composition in individuals over time. Additionally, these studies were based on non-obese individuals within normal BMI ranges, and therefore, conclusions drawn from these studies must be considered critically in regard to the obese study population, as it is unclear whether the predictive accuracy of L3/L4 carries over to higher BMI groups. The possibility of using single-slice data has also been explored for predicting weight loss in obese and overweight patients [46], and a single MRI slice was found insufficient to accurately predict weight changes over time.

Conclusion

In the present study, patients after obesity surgery were evaluated with whole-body MRI at the time of surgery, at three months postop, and at 12 months postop and showed significant absolute and relative reduction of both SAT and VAT with RYGB and LSG. Absolute reduction was higher in SAT while relative reduction was higher in VAT. Loss of SM was observed in the first three months but did not persist at 12 months. The accurate assessment of changes in tissue composition can benefit clinicians seeking to evaluate and to improve long-term patient health, as obesity and VAT in particular are indicators of patient risk for systemic cardiovascular and metabolic diseases. The method put forth in this study allows precise measurement and monitoring of tissue composition across an extended time period and can be used to compare different surgical procedures and relation with resolution of comorbidities.

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Compliance with Ethical Standards

Conflict of Interest Hans-Ulrich Kauczor reports grants, personal fees, and non-financial support from Siemens, grants and personal fees from Philips, personal fees from Boehringer Ingelheim, and personal fees from Bracco, outside the submitted work.

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 Informed consent was obtained from all individual participants included in the study.

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