

Bone Metabolism After Bariatric Surgery

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ABSTRACT

Bariatric surgery is a popular and effective treatment for severe obesity but may have negative effects on the skeleton. This review summarizes changes in bone density and bone metabolism from animal and clinical studies of bariatric surgery, with specific attention to Roux-en-Y gastric bypass (RYGB), adjustable gastric banding (AGB), and sleeve gastrectomy (SG). Skeletal imaging artifacts from obesity and weight loss are also considered. Despite challenges in bone density imaging, the preponderance of evidence suggests that bariatric surgery procedures have negative skeletal effects that persist beyond the first year of surgery, and that these effects vary by surgical type. The long-term clinical implications and current clinical recommendations are presented. Further study is required to determine mechanisms of bone loss after bariatric surgery. Although early studies focused on calcium/vitamin D metabolism and mechanical unloading of the skeleton, it seems likely that surgically induced changes in the hormonal and metabolic profile may be responsible for the skeletal phenotypes observed after bariatric surgery. © 2014 American Society for Bone and Mineral Research.

KEY WORDS: BARIATRIC SURGERY; DXA; BIOCHEMICAL MARKERS OF BONE TURNOVER; OBESITY

Introduction

Bariatric surgery is the most effective treatment for severe obesity (as defined by body mass index [BMI] $>40 \text{ kg/m}^2$), leading to sustained weight loss, marked improvements in associated comorbidities such as diabetes, hypertension, and obstructive sleep apnea, and a decrease in mortality.^(1,2) Although rates of obesity may have plateaued in recent years, the subpopulation of severely obese people continues to rise,⁽³⁾ such that 1 in 20 American adults is now morbidly obese.⁽⁴⁾ Increasing evidence suggests that patients with lower BMIs may also benefit from these procedures.⁽⁵⁾ Not surprisingly, the number of bariatric surgeries is steadily increasing, with a doubling in the number of adult bariatric surgeries performed worldwide over the past decade.⁽⁶⁾ Currently, the most commonly performed procedure is the Roux-en-Y gastric bypass (RYGB), comprising nearly half of all bariatric surgeries, followed in popularity by sleeve gastrectomy (SG) and adjustable gastric banding (AGB) (Fig. 1).

Although most long-term metabolic consequences of bariatric surgery are favorable, the effects of bariatric surgery on the skeleton appear to be harmful. Given the increasing popularity of these procedures and the likelihood for continued expansion to less obese patients,⁽⁵⁾ it is important to understand potential negative effects on bone metabolism.

This review summarizes currently available data on skeletal changes in clinical and animal studies of bariatric surgery, including a discussion of controversies over skeletal imaging artifacts in obese patients undergoing substantial weight loss.

Data from adolescents and older populations are reviewed, along with a discussion of long-term outcomes and clinical implications. Potential mechanisms explaining bone loss after bariatric surgery are briefly considered, although these remain in the realm of hypotheses and require further study. For this review, PubMed articles were reviewed through January 1, 2014, using the search terms "bariatric surgery," "gastric bypass," "gastric sleeve," "sleeve gastrectomy," "gastric banding," "bone," and "fracture." References from the retrieved articles and publications available in the author's library were also used.

Early Studies of Intestinal Surgery and Effects on the Skeleton

Initial concerns about skeletal health were based on older studies of postgastrectomy patients that demonstrated a high prevalence of osteoporosis and increased fracture risk, although it was unclear whether this was a consequence of the surgery or the result of underlying comorbidities of the patients.^(7–9) However, large animal models of gastrectomy revealed calcium malabsorption, secondary hyperparathyroidism, and progressive bone loss,⁽¹⁰⁾ lending credence to the idea that the surgical manipulation of the gut directly affects bone metabolism. In addition, jejunoileal bypass and biliopancreatic diversion, early versions of bariatric surgery involving more extensive intestinal bypass, were both associated with significant bone loss^(11,12) and histomorphometric changes consistent with osteomalacia and trabecular bone loss.^(13–16)

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	RYGB	AGB	SG
Proportion of worldwide bariatric surgeries	47%	18%	28%
Excess weight loss	63%	34%	51%
Diabetes remission	93%	68%	86%
Hypertension remission	78%	64%	82%
Obstructive sleep apnea remission	95%	71%	91%

Fig. 1. Diagram of bariatric surgery procedures and outcomes. The diagram depicts the surgical procedure for Roux-en-Y gastric bypass (RYGB), adjustable gastric band (AGB), and sleeve gastrectomy (SG) (adapted with permission from Pories WJ, JCEM 2008;93(11):S89–S96). Dark gray shading indicates the postsurgical gastrointestinal route for passage of food. Dotted lines represent the excised gastric fundus after SG. The table below summarizes the worldwide popularity,⁽⁶⁾ average excess weight loss, and improvements in comorbidities associated with the different procedures.⁽¹¹⁾

Bone Outcomes in Clinical Studies of Bariatric Surgery

Clinical studies have examined skeletal endpoints after a variety of modern bariatric surgery procedures, although the bulk of the published literature is with RYGB. Longitudinal studies document striking bone loss (Table 1) and increases in bone turnover markers (Table 2) after bariatric surgery. However, these clinical studies suffer from a number of limitations. The majority of the prospective longitudinal studies are small in size; only two cohorts with dedicated spine and hip bone density scans have ≥ 50 surgical subjects.^(17,18) Only a handful of studies^(19–21) have a nonsurgical comparator group to serve as controls for age-related changes or measurement drifts.^(19–21) In addition, there are only a few comparative studies to quantify rates of loss between different bariatric surgery procedures,^(19,22,23) of which only one trial involves randomization to remove concerns of referral bias.⁽²²⁾ Several longitudinal studies lack preoperative measurements of bone density and therefore can only describe skeletal changes in the postoperative period.^(24,25) Lastly, although there are a few RYGB studies that utilize more advanced bone imaging technology,^(20,26,27) all studies of SG and AGB rely solely on dual-energy X-ray absorptiometry (DXA) bone density measurements that may be affected by soft tissue artifact related to weight loss (see “Controversies regarding skeletal imaging after bariatric surgery” below). With these caveats in mind, the results of metabolic bone studies in bariatric surgery patients are summarized below, by surgery type. The effects of bariatric surgery on spine and hip bone mineral density (BMD) are also summarized in Figs. 2 and 3.

Roux-en-Y gastric bypass (RYGB)

RYGB involves the creation of a 30cc proximal gastric pouch that is anastomosed directly to the proximal jejunum, thus bypassing the greater portion of the stomach and duodenum (Fig. 1).⁽²⁸⁾ RYGB has been the most popular form of bariatric surgery performed worldwide in the past decade⁽⁶⁾ and is associated with an average 43 kg weight loss and BMI decrease of 17 kg/m².⁽²⁹⁾

Case reports have identified bone pain, height loss, and hypocalcemia,⁽³⁰⁾ as well as histologically confirmed osteomalacia⁽³¹⁾ and osteitis fibrosa cystica⁽³²⁾ after RYGB. Numerous studies document elevated urinary and serum bone turnover markers,^(17,19,20,23–26,33–43) beginning as early as 3 months after surgery^(19,34,35,42,43) that remain elevated throughout the second postoperative year^(19,36,44) (Table 2). The typical increase in bone resorption markers far exceeds the increase in bone formation, consistent with net bone loss.

In the last decade, numerous longitudinal studies describe striking declines in bone density by DXA after RYGB^(17–20,22–26,33–35,39,45–48) (Table 1, Fig. 2, and Fig. 3). The longest of these studies describes changes in bone density over 3 years in 62 women, a quarter of whom were postmenopausal.⁽¹⁸⁾ 1 year after RYGB, women experienced bone loss at the spine (–3%) and femoral neck (–10%), despite unchanged serum 25-hydroxyvitamin D and PTH levels. Between years 1 and 3, there were additional declines in spine (–3%) and femoral neck (–3%) bone density despite mild weight regain.

Multiple studies have reported that DXA-measured hip BMD declines faster than spine BMD in the first year after RYGB, with rates of hip bone loss ranging from 5% to 11%.^(17,20,23,26,33–35,45–47) Most studies,^(19,20,23,33,35,45–47) but not all,^(17,26,34) have reported that lumbar spine BMD falls by 3% to 7% at 1 year. Similarly, whole-body BMD declines by 2% to 5% at 1 year in most,^(19,22,35,39,46–48) but not all,^(17,20) studies. Variable effects on forearm bone density have been observed, with no change at the 1/3 distal radius site,^(20,23,26,34,35) and decreases in bone density at the ultradistal^(23,24,27) and total forearm⁽⁴⁵⁾ sites after RYGB.

Nearly all of the aforementioned studies utilized DXA technology to assess bone loss, but DXA may be confounded by artifact in obesity and with weight loss (see “Controversies regarding skeletal imaging after bariatric surgery”). Only one study has evaluated change in axial BMD using alternative bone imaging, namely quantitative computed tomography (QCT).⁽²⁰⁾ In this study of RYGB patients and matched obese controls, declines in lumbar spine BMD in the first year after surgery were concordant between DXA (–3.3%) and QCT (–3.4%) techniques. However, QCT did not detect any significant changes in total hip

Table 1. Summary of Longitudinal Studies Documenting Changes in DXA-Measured Bone Mineral Density (BMD) Before and After Bariatric Surgery

Study	No.	Female (%)	Age (years)	Time points after bariatric surgery	Spine	Total hip	Femoral neck	Whole body	1/3 radius	Notes
Roux-en-Y gastric bypass (RYGB)										
Von mach 2004 ⁽¹⁹⁾	4	100%	Mean age 45	24 months	-12.8%			-3.5%		Comparison group: AGB (n = 9); RYGB BMD loss significantly greater than AGB group at both sites; vertebral BMD assessed on whole-body scan
Coates 2004 ⁽³⁵⁾	15	80%	Not specified	9 months	-3.3%	-7.8%	-5.1%	-1.6%	NS	
Johnson 2005 ⁽⁴⁵⁾	23	80%	Mean age 39 for women, mean age 43 for men	12 months	-4.5%	-9.3%	-9.3%			Total forearm decline -1.9% at 12 months; entire cohort n = 233 but only 23 had radius/spine/hip DXA; changes at 24 months (n = 14) and 36 months (n = 8) were NS
Olbiers 2006 ⁽²²⁾	29	76%	Mean age 37	12 months				-2.4% ^a		Randomized comparison group: VBG (n = 46); RYGB BMD loss significantly greater than VBG group; entire RYGB cohort n = 37 but only 29 with DXA
Fleischer 2008 ⁽³⁴⁾	23	78%	Age range 20-64	12 months	NS	-9.2%	-8.0%		NS	
Mahdy 2008 ⁽⁵⁹⁾	70	70%	Mean age 45; range 18-51	12 months	-7.4%	-10.5%		-3.2%		
Carrasco 2009 ⁽⁴⁷⁾	42	100%	Mean age 38; range 19-55	12 months	NS	-8.0%		-3.0%		
Carlin 2009 ⁽¹⁷⁾	30 (randomized to vit D 50,000 IU/wk)	100%	Mean age 43	12 months	NS	-12.0%		NS		
Nogues 2010 ⁽²³⁾	7	100%	Mean age 46	12 months	-6.3%	-11.1%	-10.8%		NS	12-month data also published in Vilarasa 2009 ⁽⁴⁶⁾
Vilarasa 2011 ⁽¹⁸⁾	62	100%	Mean age 46	12 months	-3.2%		-10.2%	-1.9% ^b		Rate of decline twice as high in postmenopausal women compared with premenopausal women
Kaulfers 2011 ⁽⁴⁸⁾	59			12-36 months	-3.1% additional decline		-2.7% additional decline			Baseline scan occurred from 0-6 months after RYGB; follow-up scan time point varied (range 3-27 months); regression modeling used to predict % change at 12 mo
	61	84%	Mean age 17; range 14-24	12 months (based on regression modeling)				-5.2% ^c		
Casagrande 2012 ⁽³³⁾	22	100%	Mean age 37	12 months	-7.3%	-8.6%	-8.8%		NS	
Yu 2013 ⁽²⁰⁾	30	87%	Mean age 47; range 20-75	12 months	-3.3%	-8.9%	-6.1%	NS		Control group: nonsurgical obese (n = 20); RYGB BMD loss significantly greater than controls at all sites
Stein 2013 ⁽²⁶⁾	14	100%	Mean age 45	12 months	-3.2% (by QCT)	NS (by QCT)	NS (by QCT)		NS	QCT vBMD also obtained in RYGB and controls; RYGB QCT vBMD loss significantly greater than controls at spine but not different at hip
Adjustable gastric banding (AGB)										
Strauss 2003 ⁽⁵³⁾	17	88%	Mean age 43; range 28-58	Mean 30 months, range 15-39 months	NS			NS		Smaller BMD changes in full cohort (n = 22) including RYGB (n = 14), AGB (n = 6) and SG (n = 2); data for RYGB group shown here; HR-pQCT data also reported
Von mach 2004 ⁽¹⁹⁾	9	67%	Mean age 41	24 months	NS			3.0%		Comparison group: RYGB (n = 6); RYGB BMD loss significantly greater than AGB group at both sites; vertebral BMD assessed on whole-body scan
Giusti 2005 ⁽⁵⁰⁾	37	100%	Median age 35; range 24-52	12 months	3.5%	-8.1%	-2.3%	NS		12-month data in subset also published in Pugnale 2003 ⁽⁵¹⁾
Dixon 2007 ⁽²¹⁾	26	76%	Mean age 42	24 months	NS		-5.8%	NS		Comparison group: medical weight loss (n = 27); bone loss in AGB group and medical group were similar
Nadler 2009 ⁽⁵⁴⁾	36	67%	Mean age 16; range 14-18	12 months				-2.8% ^c		
DI Renzo 2011 ⁽⁵²⁾	40	70%	Mean age 44	6 months				5.8% ^a		
Sleeve gastrectomy (SG)										
Nogues 2010 ⁽²³⁾	8	100%	Mean age 50	12 months	-4.6%	-7.1%	-8.3%		NS	
Pluskiewicz 2012 ⁽⁵⁸⁾	29	100%	Mean age 40	6 months	-1.2%	-5.2%	-7.0%			
Ruiz Tovar 2013 ⁽⁵⁹⁾	42	93%	Mean age 44; range 20-62	12 months	5.7%					
	30			24 months	7.9%			-6.1% ^a		

NS = not statistically significant. BMD = bone mineral density; BMC = bone mineral content.

Cross-sectional studies and/or longitudinal studies missing preoperative baseline data are not included.

^aPercent change estimated from mean values at baseline and follow-up.^bPercent change estimated from figure.

Table 2. Summary of Longitudinal Studies Documenting Changes in Bone Turnover Markers Before and After Bariatric Surgery

Study	No.	Female (%)	Age (years)	Time points after bariatric surgery	Bone formation markers			Bone resorption markers			Notes
					Serum P1NP	Serum OC	Serum BSAP	Urinary or serum NTX	Serum CTX	Urinary DPD	
Roux-en-Y gastric bypass (RYGB)											
Von mach 2004 ⁽¹⁹⁾	4	100%	Mean age 45	0, 3, 6, 12, 24 ^a months	218% ^b					71% ^b	At 3 mo: DPD 153% ^b , OC NS; at 6 mo: DPD 58% ^b , OC 191% ^b ; at 12 mo: DPD 65% ^b , OC 218% ^b ; significantly different from AGB and controls at 24 mo
Coates 2004 ⁽³⁵⁾	15	80%	Not specified	3, 9 ^a months			NS	319% urinary			At 3 mo: NTX +174%, OC NS
ElKadre 2004 ⁽⁴⁰⁾	30 (premenopausal)	100%	Not specified	12 months			53% ^a				No statistics presented; unclear whether changes in BSAP were statistically significant
	30 (postmenopausal)	100%	Not specified	12 months			100% ^a				No statistics presented; unclear whether changes in BSAP were statistically significant
Riedt 2006 ⁽³⁷⁾	21	100%	Mean age 44, range 29–62	6 months				62% serum		204%	Urinary pyridinolines 16.4%
Riedl 2008 ⁽³⁸⁾	30	90%	Mean age 43	12 months	183% ^a				190% ^a		Compared with AGB group: change in OC and CTX numerically greater but not statistically different from AGB group
Mahdy 2008 ⁽³⁹⁾	70	70%	Mean age 45, range 18–51	12 months			NS				
Fleischer 2008 ⁽³⁴⁾	23	78%	Range 20–64	3, 6, 12 ^a months	39%			106% urinary			At 3 mo: uNTX 57% ^a , OC 86% ^a ; at 6 mo: uNTX 103% ^a , OC 86% ^a
Carlin 2009 ⁽¹⁷⁾	30 (randomized to vit D 50,000 IU/week)	100%	Mean age 43	12 months			8%	55% urinary			
	30 (randomized to vit D 800 IU/d)	100%	Mean age 43	12 months			11%	43% urinary			
Bruno 2010 ⁽³⁶⁾	20	50%	Mean age 33, range 24–47	6 ^a , 18 months	58% ^a		15% ^a	83% serum			Different cohort of 19 adults followed for 18 mo: BSAP 29%, sNTX 59%
Nogues 2010 ⁽²³⁾	7	100%	Mean age 46	12 months			NS	111% ^a urinary			
Sinha 2011 ⁽⁴³⁾	73 (RYGB <i>n</i> = 50, AGB <i>n</i> = 18, BPD <i>n</i> = 5)	66%	Mean age 39	3, 6, 9, 12, 18 ^a months	95%		NS	50% ^c urinary			Data for combined RYGB/AGB/BPD: at 3 mo: uNTX 81%, OC 32%; at 6 mo: uNTX 52% ^c , OC 128% ^c ; BSAP NS at all time points
Casagrande 2012 ⁽³³⁾	22	100%	Mean age 37	12 months				133% ^a serum			
Yu 2013 ⁽²⁰⁾	30	87%	Mean age 47, range 20–75	6, 12 ^a months	80%		NS		199%		At 6 mo: P1NP 82%, CTX 220%, OC NS; increases in P1NP and CTX significantly greater than nonsurgical controls at 6 and 12 months
Stein 2013 ⁽²⁶⁾	14	100%	Mean age 45	12 months			20%		144%		In combined population <i>n</i> = 22 of RYGB (<i>n</i> = 14) + AGB (<i>n</i> = 6) + SG (<i>n</i> = 2): CTX 144%, BSAP NS
Biagioni 2013 ⁽⁴²⁾	22	100%	Age range 18–40	3, 6 ^a months			NS		285% ^a		At 3 mo: CTX 174% ^a , BSAP NS
Adjustable gastric banding (AGB)	9	67%	Mean age 41	3, 6, 12, 24 ^a months			NS			NS	No change in DPD or OC at any time point; lack of change significantly different from RYGB group
Von mach 2004 ⁽¹⁹⁾	21	100%	Median 35, range 24–52	6, 12, 18, 24 ^a months				62% ^a urinary	131% ^a		At 6 mo: uNTX/Cr 40% ^a , CTX 100% ^a ; at 12 mo: uNTX/Cr 61% ^a , CTX 119% ^a ; at 18 mo: uNTX/Cr 38% ^a , CTX 113% ^a
Giusti 2005 ⁽⁵⁰⁾	21	100%	Median 35, range 24–52	24 ^a months							Compared with RYGB group: change in OC and CTX numerically less but not statistically different from RYGB group
Riedl 2008 ⁽³⁸⁾	10	80%	Mean age 44	12 months	68%				128% ^a		
Sleeve gastrectomy (SG)											
Nogues 2010 ⁽²³⁾	8	100%	Mean age 50	12 months			–16% ^a	140% ^a urinary			

NS = not statistically significant.

Cross-sectional studies and/or longitudinal studies missing preoperative baseline data are not included.

*When multiple time points were studied, starred time point is reported in table.

^aPercent change estimated from mean values at baseline and follow-up.

^bPercent change estimated from figure.

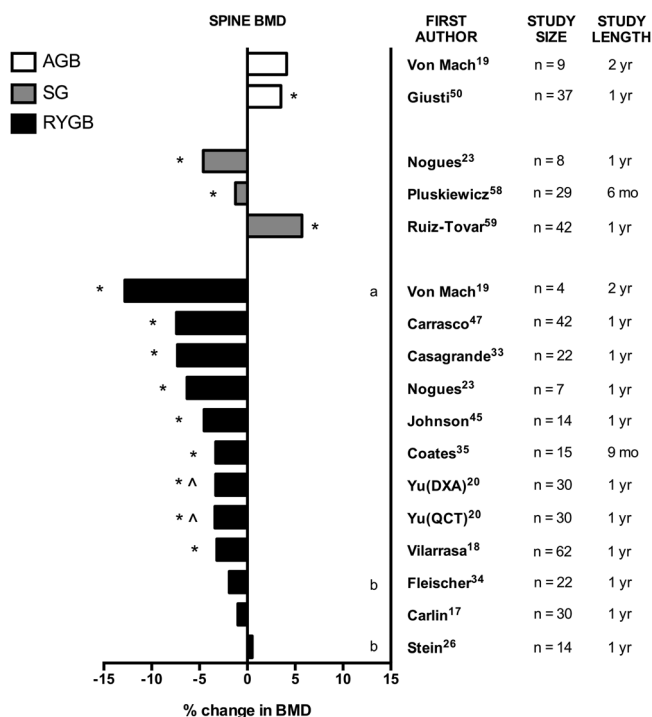


Fig. 2. Percent change in spine bone mineral density (BMD) after bariatric surgery. Graphical summary of data from longitudinal studies of bariatric surgery, by surgery type. Unless otherwise indicated, percent change is measured by DXA at lumbar spine from preoperative baseline to postoperative time point after RYGB, SG, or AGB. Study size (*n*) and study length (mo = months, yr = years) are noted. In one study, percent change as measured by quantitative computed tomography (QCT) is also reported. *Statistically significant compared with baseline (within-group comparison). ^Statistically significant compared with control group (between-group comparison). a = vertebral BMD was assessed by total body DXA. b = values are estimated from published figures.

and femoral neck BMD measurements after RYGB, despite significant declines in these measurements by DXA (total hip -8.9%, femoral neck -6.1%). Within the trabecular compartment of the hip, QCT did detect bone loss (total hip -4.6%, femoral neck -3.0%), but the magnitude remained smaller than DXA. The reason for this discrepancy is not clear but certainly highlights that the accuracy of bone density imaging modalities may be adversely affected by changes in body composition.

Two studies have evaluated changes in peripheral bone density after RYGB using high-resolution peripheral QCT (HR-pQCT).^(26,27) HR-pQCT is able to assess changes in cortical and trabecular microarchitecture and volumetric BMD (vBMD). Both HR-pQCT studies found that RYGB led to significant declines in total vBMD at the radius and the tibia, as well as reduced cortical vBMD and cortical thickness in the year after bariatric surgery. Microarchitectural changes were consistent with endocortical resorption and were more pronounced at the tibia than at the radius. This high-resolution technique also permits evaluation of cortical porosity, which increased by 30% after RYGB.⁽²⁷⁾ Lastly, microfinite element analysis of the HR-pQCT data suggested a decline in estimated bone strength at the tibia.⁽²⁷⁾ Taken together, these central and peripheral QCT studies verify that RYGB induces significant bone loss at the lumbar spine, distal

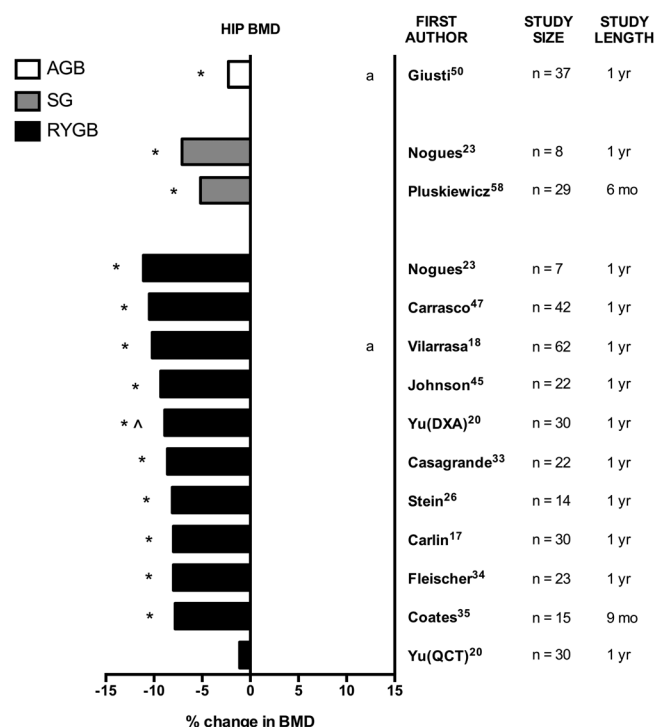


Fig. 3. Percent change in hip bone mineral density (BMD) after bariatric surgery. Graphical summary of data from longitudinal studies of bariatric surgery, by surgery type. Unless otherwise indicated, percent change is measured by DXA at the total hip from preoperative baseline to postoperative time point after RYGB, SG, or AGB. Study size (*n*) and study length (mo = months, yr = years) are noted. In selected studies, alternative imaging techniques (QCT = quantitative computed tomography) or alternative hip sites (ie, femoral neck) are noted. *Statistically significant compared with baseline (within-group comparison). ^Statistically significant compared with control group (between-group comparison). a = % change in femoral neck BMD is shown as total hip BMD results were not reported.

radius, and distal tibia. Further studies are required to determine whether imaging artifacts confound femoral bone loss measurements in the first year after RYGB.

Adjustable gastric banding (AGB)

AGB is a purely restrictive procedure that involves placement of an inflatable band high in the stomach to produce a gastric pouch of ~30cc (Fig. 1).⁽²⁸⁾ AGB is associated with less initial weight loss and more weight regain compared with RYGB, although long-term weight loss maintenance still far exceeds nonsurgical methods.⁽⁴⁹⁾ AGB is now the third most common bariatric procedure performed worldwide.⁽⁶⁾

Although there are fewer studies of this technique, the magnitude of skeletal effects observed after restrictive procedures such as AGB appear to be less than what is observed after RYGB, with less impressive increases in bone resorption markers^(19,38,50) (Table 2), lower rates of femoral bone loss⁽⁵⁰⁾ (Table 1, Fig. 3), and a paradoxical sparing or even increase in spine BMD^(19,50) (Table 1, Fig. 2).

For example, only one AGB cohort (*n* = 37) has been longitudinally evaluated with DXA scans at spine and hip sites.

Results at both 1 year⁽⁵¹⁾ and at 2 years⁽⁵⁰⁾ demonstrate decreases in femoral neck BMD (0 to 1 year -2.3% ; 0 to 2 years -5.8%) but no change in lumbar spine BMD at 2 years. These BMD changes were observed in conjunction with increases in both urine N-telopeptide and serum C-telopeptide ($+62\%$ and $+131\%$, respectively), and occur despite increases in 25-hydroxyvitamin D and decreases in parathyroid hormone. One additional study found an increase in spine BMD ($+3\%$, as assessed on whole-body scan) 2 years after AGB.⁽¹⁹⁾ In the absence of a control group, it is unknown whether this increase represents a true increase in spine BMD as a consequence of AGB or an artifact of degenerative change with aging.

There are contradictory data regarding effects of AGB on whole-body bone mineral content and density, with several studies finding bone loss within the first 2 years,^(21,52) others finding no change in bone density over variable follow-up time,^(50,53) and two additional studies finding increased bone density at 2 years.^(19,54) In one of the studies, the significant decline in whole-body BMD was similar to the decline in a control group randomized to nonsurgical weight-loss methods,⁽²¹⁾ suggesting that the observed changes in whole-body bone may not be a direct consequence of the AGB procedure.

Interestingly, a similar pattern of mild femoral bone loss with relative sparing of spine and whole-body BMD was also observed with vertical banded gastroplasty (VBG), a surgical precursor to AGB.^(22,55,56) This suggests that restrictive bariatric procedures may share a skeletal phenotype that is distinct from other types of bariatric surgeries.

Sleeve gastrectomy (SG)

SG involves creation of a narrow gastric tube through excision of the body of the stomach (Fig. 1).⁽²⁸⁾ It produces weight-loss effects that are slightly less than RYGB but is associated with similar improvements in metabolic endpoints and lower complication rates.⁽⁵⁷⁾ Sleeve gastrectomy is a relatively new bariatric procedure but has skyrocketed in popularity, with a fourfold increase in surgical procedures between 2008 and 2011.⁽⁶⁾ Also known as vertical sleeve gastrectomy or gastric sleeve, this procedure is now the second most commonly performed bariatric procedure worldwide.⁽⁶⁾ Given the relatively recent rise of SG, only a few studies have examined the effect of this procedure on skeletal endpoints.

Two longitudinal studies found significant declines in bone density at axial sites, with average DXA-measured femoral bone loss (range -5.2 to -8.3%) exceeding average spine bone loss (range -1.2% to -4.6%) within the first year after SG^(23,58) (Table 1, Fig. 2, and Fig. 3). In contrast, a third study found significant increases in spine BMD over 2 years ($+7.9\%$).⁽⁵⁹⁾ The reasons for the discrepant results at the lumbar spine are unclear, although the last study had remarkable improvements in vitamin D deficiency (prevalence of 95% preoperatively to 2% postoperatively)⁽⁵⁹⁾ as compared with most other studies that have documented either stability or worsening of vitamin D deficiency and secondary hyperparathyroidism after bariatric surgery.

One small study compared SG ($n = 8$) to RYGB ($n = 7$) and found that bone loss at all sites appeared to be less after SG compared with RYGB, but the analysis lacked power to find statistically significant differences between groups.⁽²³⁾ One cross-sectional study found that lumbar spine and femoral neck BMD were similar in SG and RYGB groups 12 months after surgery.⁽⁶⁰⁾ Unfortunately, this analysis lacked preoperative DXA scans to interpret differences in rates of bone loss. Coupled with data

from animal studies,⁽⁶¹⁾ it appears that the rate of bone loss after SG is slightly less than that observed with RYGB, although additional data are needed.

Bariatric surgery and bone health: adolescent and older populations

The majority of the studies published to date focus on a premenopausal female population. This is a reflection of the population that had been seeking bariatric surgery up until the early 2000s. In a meta-analysis published in 2004, 73% of bariatric surgery patients were female, with an average age of 39 years.⁽²⁹⁾ In recent years, bariatric surgery procedures have become increasingly utilized at both ends of the age spectrum, each of whom have unique considerations with regard to skeletal health. There has been a steep increase in the number of adolescent bariatric surgery procedures performed in the last decade.^(62–64) Yet, only two studies have examined the effect of bariatric surgery on skeletal health in adolescents (Table 1). The first of these was a retrospective study that estimated a 7.4% decline in whole-body bone mass 2 years after RYGB.⁽⁴⁸⁾ This decline exceeds the typical rate of whole-body bone loss described after RYGB in adult studies. Nevertheless, the average BMD Z-score remained above 0, indicating that average BMD remained higher than age-matched controls. In contrast, another longitudinal study of adolescents who had undergone AGB found an increase in whole-body bone mass over 1 year, similar to adult studies that suggest lesser skeletal effects after AGB.^(19,52,54) There have been no studies examining changes in hip and spine BMD in adolescents after bariatric surgery. Ultimately, the long-term implications of altering bone metabolism in a young population that has yet to achieve peak bone mass are unclear.

On the other end of the age spectrum, the percentage of patients aged 60 years or older now exceeds 10% of the bariatric surgery population.⁽⁶⁵⁾ Given expected age-related declines in bone density, the clinical significance of surgically induced bone loss in older adults may be greater. Not surprisingly, postmenopausal women have higher postoperative rates of osteopenia and osteoporosis compared with premenopausal women.⁽⁶⁶⁾ Furthermore, bone markers^(40,67) and rates of bone loss⁽¹⁸⁾ are twice as high in postmenopausal women compared with premenopausal women. If confirmed in additional studies, these results suggest that advanced age and/or a low-estrogen state may compound the risk of bariatric surgery-induced bone loss.

Controversies Regarding Skeletal Imaging After Bariatric Surgery

One practical limitation to the evaluation of skeletal health after bariatric surgery is the difficulty in obtaining accurate and reproducible bone density scans in severely obese patients and during weight loss. Challenges include both logistic and technical problems, and may be specific to certain techniques and bone sites. For example, measurements at axial sites (eg, spine, hip) may be more difficult to obtain and to interpret than appendicular measurements (eg, radius, tibia, calcaneus), which are not subject to weight requirements and have less overlying soft tissue to cause artifact.

Logistic hurdles involve practical limitations in obtaining usable DXA scans in obesity because of weight and/or body size. Until recently, standard DXA scanners only had a table weight capacity of 350 lb (160 kg). Although newer models now support

weights up to 450 lb (205 kg), severely obese patients may also exceed table widths, thus requiring offset scanning or manual imputation to calculate whole-body measurements.⁽⁶⁸⁾ Furthermore, in our personal experience, many spine and hip scans in patients >400 lb (182 kg) are unreadable because of decreased penetration of photons through soft tissue, and as evidenced by tissue thickness scores above manufacturer-recommended thresholds.

Amongst those scans that are obtainable and readable, there remain technical issues related to the unpredictable impact of soft tissue artifact on bone density imaging techniques. It is well known that DXA bone density measurements are subject to accuracy errors because of changing body composition, as studied in both phantom-based⁽⁶⁹⁾ and human clinical studies of fat layering.^(70–74) The magnitude and direction of the BMD artifacts can be unpredictable, and vary by pencil-beam or fan-beam technology and by DXA manufacturer. Furthermore, the precision error of BMD measurements by DXA increases with increasing BMI.⁽⁷⁵⁾ These technical artifacts pose complications for both cross-sectional studies of obese patients and for longitudinal studies that involve significant weight loss. Given that bariatric surgery procedures are accompanied by an average 88 lb (40 kg) weight loss,⁽²⁹⁾ it is possible that these large weight changes may be adversely affecting DXA measurements.

These technical difficulties stem from several potential sources of error in DXA measurements, including magnification artifact, the “two-component limitation,” and changing marrow adiposity. Magnification artifact, also known as projection artifact, is a consequence of modern fan-beam scanners. Changing the distance from the X-ray source to the bone after substantial weight loss may alter the measurement of bone area, similar to how an object casts a larger shadow as it gets closer to a light source. Several studies indeed report physiologically implausible changes in bone area after bariatric surgery,^(19,20,39) consistent with magnification artifact. Importantly, magnification artifact will not affect assessment of BMD, which is measured independently of bone area.⁽⁷⁶⁾ Nevertheless, erroneous bone area measurements will lead to incorrect values for bone mineral content (BMC), which is calculated from bone area and bone mineral density ($BMC = BMD \times \text{area}$). Another potential source of measurement error in obese patients is the “two-component limitation” of DXA, whereby assumptions about fat:lean tissue ratios are made to calculate the three densities of fat, lean tissue, and bone. These assumptions may be inaccurate in obesity and in the setting of profound weight loss. For example, DXA measurements significantly underestimate loss of body fat after RYGB compared with deuterium-based measurements.⁽⁷⁷⁾ In addition, as discussed earlier, QCT measurements of BMD after RYGB are discordant with DXA at femoral sites, with DXA demonstrating significantly greater declines in total hip and femoral neck BMD at 1 year.⁽²⁰⁾ It should be noted, however, that QCT may also be subject to beam hardening and other imaging artifacts in obesity, although the impact is thought to be less than that of DXA.⁽⁷⁰⁾ Lastly, both CT-based and DXA-based measurements of BMD may be affected by changes in marrow adiposity independent of changes in bone density.⁽⁶⁹⁾ However, little is currently known about how marrow adiposity might be affected by bariatric surgery.

Nevertheless, other clinical data suggest that bone loss after bariatric surgery is indeed occurring, even if BMD assessments are imperfect. As discussed earlier, QCT-based measurements have confirmed bone loss at the lumbar spine, radius, and tibia after RYGB.^(20,26,27) DXA imaging also suggests bone loss at the

ultradistal radius,^(23,24,27) a peripheral site that should be less subject to changing body composition. In addition, there is evidence of continued bone loss in the second and third years after bariatric surgery, after weight has stabilized, and should not be further affecting DXA measurements.^(18,19,25,45,50) Multiple studies confirm that markers of bone turnover are markedly elevated after bariatric surgery (Table 2). The typical increase in bone resorption markers exceeds that observed during the menopause transition⁽⁷⁸⁾ or even during prolonged space flight.⁽⁷⁹⁾ Lastly, bone loss has also been documented in animal models of bariatric surgery. Therefore, it is clear that bariatric surgery does cause a notable negative impact on the skeleton.

Animal Studies of Bariatric Surgery and Bone

Animal models of modern bariatric surgery procedures have been developed, largely to study the mechanisms underlying the metabolic effects of weight-loss surgery.^(80,81) Initial efforts in this area focused on evaluating surgical techniques in large animals such as in dogs⁽⁸²⁾ and pigs.⁽⁸³⁾ More recently, rodent models have been developed, including rat models of RYGB,^(84,85) gastric banding,^(86,87) and sleeve gastrectomy.^(88–90) Mouse models of bariatric surgery have also been developed^(91–93) to take advantage of the power of genetically altered mice to delineate the mechanisms underlying metabolic improvements subsequent to bariatric surgery.

Although numerous studies have used animal models to explore the mechanisms underlying the metabolic outcomes after bariatric surgery, few have examined skeletal outcomes.^(61,94–96) In general, these studies confirm bone loss after bariatric surgery, yet they are limited to date by small sample sizes, use of nonobese models, and inadequate control groups. For example, nonobese rats subjected to gastric bypass had lower *in vivo* DXA measurements of whole-body and femoral BMD compared with sham-operated controls over a 12-month period.⁽⁹⁴⁾ Nonobese type 2 diabetic rats that underwent gastrojejunum bypass had reduced femoral cortical and trabecular BMD 8 weeks after surgery compared with nonoperated controls.⁽⁹⁵⁾ However, interpretations of both of these studies are significantly limited by the lack of weight-matched control groups.

Another study compared skeletal outcomes after different bariatric surgery approaches in adult rats with diet-induced obesity.⁽⁶¹⁾ Specifically, rats that underwent gastric bypass had decreased bone volume compared with sham-operated controls, despite dietary supplementation to normalize vitamin D and calcium. In contrast, despite a similar degree of weight loss, rats that underwent sleeve gastrectomy did not exhibit bone loss compared with sham-operated groups. These results suggest that there may be physiologic changes specific to the gastric bypass procedure that induce bone loss.

Finally, a study in obese adult rats suggests that physiologic changes, and not weight loss, may be responsible for bone loss.⁽⁹⁶⁾ Obese rats that underwent RYGB had lower vertebral BMD than sham-operated controls that were weight-matched by calorie restriction. These findings were apparent by imaging as early as 2 weeks and were confirmed by histomorphometry at 14 weeks, providing evidence that the bone loss after RYGB in obese rats is not directly caused by body weight loss.

To date, despite availability of several surgical models, there have been no studies examining the skeletal effects of bariatric surgery in murine models.

Long-Term Outcomes and Fractures After Bariatric Surgery

The long-term consequences of the observed bone loss after bariatric surgery remain in dispute. It is clear that many of the early bariatric procedures were associated with calcium and vitamin D deficiencies, which led to case reports of histologically confirmed osteomalacia, osteoporosis, osteitis fibrosa cystica, and brown tumors after bariatric surgery.^(32,97–99) Since then, there has been a shift toward surgeries with less malabsorptive sequelae coupled with more aggressive vitamin and mineral supplementation, and the incidence of these case reports has declined.

Several longitudinal studies have reported that bone markers remain elevated,^(16,19,36,44,50,100,101) and bone loss may continue into the second and third years after surgery.^(18,19,25,45,48,50) Cross-sectional studies also suggest that bone markers are higher than expected even 3 years after bariatric surgery.^(24,102) However, morbidly obese patients tend to have a higher BMD preoperatively,⁽¹⁰³⁾ and therefore the clinical significance of bone loss after bariatric surgery is unclear. There are contradictory studies regarding the prevalence of osteopenia/osteoporosis after bariatric surgery, with some studies suggesting lower BMD than expected^(104–106) and others finding no difference compared with age-matched controls.^(16,18,24,102)

Only two studies have examined the risk of fractures in a bariatric surgery population.^(107,108) The first retrospective cohort study utilized the United Kingdom General Practice Research Database (GPRD) and examined 2079 patients who had undergone bariatric surgery.⁽¹⁰⁷⁾ This study did not find an increase in fracture risk for patients in the first 2 years after bariatric surgery compared with weight-matched obese controls. However, 2/3 of the cohort had undergone AGB, the procedure associated with the least amount of bone loss in longitudinal studies. In addition, this study was limited by the young age of the cohort (44.6 years old) and relatively short follow-up time (2.2 years). Although there was a trend toward increased risk of fracture 3 to 5 years after surgery, there were limited data at these later time points and these results were not statistically significant.

In contrast, a retrospective study from the Rochester Epidemiology Project determined that bariatric surgery patients had a twofold increased risk of fracture compared with community-based incidence rates (standardized incidence ratio 2.3 [95% confidence interval (CI) 1.8–2.8]),⁽¹⁰⁸⁾ including an increase in vertebral (3.1 [1.4–5.9]), femoral (5.5 [1.5–14]), proximal humerus (5.0 [2.2–9.0]), and leg fractures (2.4 [1.5–3.7]). Important differences from the UK GPRD study include a smaller number of subjects ($n=258$) but longer follow-up time (8.9 years) and a predominance of RYGB procedures (75%) in the Rochester cohort. In addition, this study did not compare the bariatric surgery cohort to a weight-matched cohort and thus was unable to determine whether the increased fracture risk was a direct consequence of the bariatric surgery or was attributable to underlying obesity, which often persists even after surgical weight loss. Some studies have suggested that obesity may be independently associated with increased fracture risk at certain sites,^(109–111) although other studies have not found this association.^(112,113)

Clinical Implications and Management of Skeletal Health in Bariatric Surgery Patients

There are important practical considerations regarding the prevention of bone loss and fractures in patients who have

undergone bariatric surgery. Despite considerable weight loss, many morbidly obese patients continue to have body mass indices in the obesity range after surgery.⁽¹⁾ Obese patients and those who have undergone bariatric surgery may be at higher risk of falls, and may also be at higher risk of injury as a consequence of falls.^(114,115) In addition, obese patients tend to fracture at higher bone density⁽¹¹⁶⁾ and lower FRAX scores⁽¹¹⁷⁾ than their normal-weight peers, suggesting that different treatment cut-offs may be necessary to identify obese patients at risk of fracture. Despite these difficulties in bone density interpretation, experts have generally recommended DXA scans at baseline and every 1 to 2 years after bariatric surgery until BMD measurements stabilize.^(118–120)

Calcium and vitamin D supplements are recommended for all patients who have undergone bariatric surgery, with recent guidelines suggesting 1200 to 1500 g/d of calcium citrate and 3000 IU/d of vitamin D.⁽¹¹⁸⁾ Note, however, that supplementation amounts vary significantly between patients,^(118,121) with many patients requiring significantly higher doses (as much as 50,000 IU/d) to maintain vitamin D sufficiency and avoid secondary hyperparathyroidism. The reason for this discrepancy in requirements remains unclear but accentuates the importance of regular monitoring of calcium, 25-hydroxyvitamin D, and parathyroid hormone levels in bariatric surgery patients. As for osteoporosis medications, there is currently no consensus on who should receive treatment, but it is generally advisable to consider treatment in osteoporotic patients and those with high fracture risk. Importantly, there are no studies that have specifically evaluated the efficacy of osteoporosis treatments in a bariatric surgery population. Post hoc analyses suggest that some,^(122,123) but not all,⁽¹²⁴⁾ antiresorptive agents may have reduced efficacy in overweight and obese patients. After bariatric surgery, the bioavailability of oral osteoporosis medications may be further reduced, and concerns have been raised about possible negative effects of oral bisphosphonates on erosion of surgical gastrointestinal anastomoses. Most importantly, until the mechanisms of bone loss after bariatric surgery have been elucidated, it remains unclear whether standard osteoporosis treatments will be efficacious to prevent bone loss and/or fracture. If antiresorptive treatments are utilized, it is important to note that bariatric surgery patients receiving bisphosphonates or denosumab may be at higher risk of developing hypocalcemia.⁽¹²⁵⁾ In general, those who are at higher risk of complications from bone loss should be monitored more aggressively, notably adolescents, older populations, and those starting with low bone density or who have other risks for fracture at baseline.

Mechanisms of Bone Loss After Bariatric Surgery

The mechanisms of bone loss after bariatric surgery are currently unknown but are likely multifactorial. Secondary hyperparathyroidism owing to vitamin D deficiency and mechanical unloading owing to weight loss are among the most commonly cited potential mechanisms underlying bone loss after bariatric surgery, yet data does not support these hypotheses. New hypotheses involving crosstalk between the skeleton and gastrointestinal, adipocytic, and neurohormonal systems are now being explored.

Early explanations of bariatric surgery-induced bone loss centered on calcium and vitamin D malabsorption. RYGB bypasses the duodenum and proximal jejunum, the primary sites of calcium absorption, and may lead to malabsorption of fat-soluble vitamins such as vitamin D.⁽¹²⁶⁾ Indeed, calcium

absorption declines after gastric bypass surgery, but preoperative absorption efficacy is relatively high such that postoperative values remain within the normal range.⁽³⁷⁾ Importantly, both animal⁽⁶¹⁾ and clinical^(17,20,25,33,35,39,46) studies have documented striking declines in BMD and increases in bone turnover markers even in the absence of significant changes in circulating vitamin D or PTH. These data clearly indicate that other mechanisms must explain the majority of the bone loss seen after bariatric surgery.

Another commonly cited mechanistic hypothesis for metabolic bone changes is mechanical unloading of the skeleton owing to drastic weight loss after bariatric surgery. Some,^(26,34,47) but not all,⁽²⁰⁾ studies have found an association between bone loss and weight loss, and two studies have found that bone loss and lean mass loss are correlated.^(18,35) Although these associations might reflect the impact of mechanical unloading on the skeleton, it is also possible that it might be because of limitations of DXA-based BMD measurements in the setting of changing body composition. Furthermore, as discussed earlier, bone loss and elevations in bone markers persist despite weight stabilization in subsequent years after bariatric surgery. Lastly, animal studies have found that the rapid bone loss seen after RYGB is not observed in weight-matched calorie-restricted controls,⁽⁹⁶⁾ strongly suggesting that weight loss is not the underlying mechanism of skeletal changes.

Other regulatory mechanisms are now being explored to explain the observed bone loss after bariatric surgery. Indeed, there is a push to rename bariatric procedures as “metabolic surgeries,” to highlight that improvements extend beyond simple weight loss and are likely mediated by changes in the hormonal profile after surgery. Bariatric surgery is associated with dramatic changes in gut-derived hormones, such as ghrelin, GLP-1, and PYY, as well as changes in bile acid metabolism.⁽¹²⁷⁾ Similarly, the large alterations in body composition after bariatric surgery are accompanied by changes in estradiol and adipocytic hormones (eg, leptin, adiponectin, visfatin, resistin).^(128,129) There are data to suggest that some of these hormones may have direct effects upon bone homeostasis.^(130,131) Lastly, increased energy expenditure has been documented after bariatric surgery,⁽¹³²⁾ as well as metabolic changes such as metabolic acidosis.⁽⁹⁶⁾ Many of these hormonal and metabolic effects may contribute to the observed changes in bone after bariatric surgery, although these hypotheses remain exploratory at this time. It is also possible that the discrepancies in bone metabolism after the various bariatric procedures may be in part explained by the different impact of these surgeries on the neurohormonal and metabolic profile. For a more in depth consideration of exploratory hypotheses relating bone and hormonal changes after bariatric surgery, refer to published reviews.^(133–135)

Conclusions

The worldwide obesity epidemic has led to increasing utilization of bariatric surgery procedures. Although these procedures have beneficial effects on many cardiometabolic outcomes, the possible negative effects on bone metabolism and long-term skeletal health must be examined. Despite challenges in bone density imaging, the preponderance of evidence suggests that modern bariatric surgery procedures have negative effects on bone homeostasis that persist for at least several years, and that these effects vary by surgical type. In particular, the negative skeletal effects of RYGB and SG appear to be much greater than

for purely restrictive procedures such as AGB. The clinical implications for osteoporosis and fracture risk are still unclear, but treatment recommendations for all patients undergoing bariatric surgery includes aggressive calcium and vitamin D supplementation and serial bone density monitoring.

Future directions for research include further utilization of multiple bone density imaging modalities to verify the magnitude of bone loss after bariatric surgery, longitudinal studies to evaluate long-term effects of bariatric surgery on bone metabolism and risk of fractures, and additional focus on susceptible populations who are increasingly seeking bariatric surgery, including adolescents and the elderly. Lastly, it is imperative to understand the mechanisms by which bariatric surgery leads to bone loss, and whether these mechanisms vary according to the specific surgical intervention. This information will not only lead to a better understanding of potential treatments for bone loss but will also be an important step toward unraveling the fascinating and complex interactions between bone, gut, fat, muscle, and brain.

Disclosures

The author states that she has no conflicts of interest.

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