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ORIGINAL ARTICLE

Impact of bariatric surgery on carotid intima-media thickness and arterial stiffness in metabolically healthy obesity: a prospective study

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Abstract

Purpose Cardiovascular disease is one of the leading causes of mortality in patients with obesity. Metabolically healthy obesity (MHO), in which people do not have metabolic disorders, is a transient state of obesity. However, over the long term, a proportion of individuals with MHO develop metabolic syndrome (MetS). We aimed to investigate the effect of substantial weight loss following bariatric surgery in MHO on carotid intima-media thickness (CIMT) and pulse-wave velocity (PWV), which are independent predictors of subclinical atherosclerosis.

Methods This prospective study included 38 patients (34 women, four men) undergoing bariatric surgery who had severe obesity but without comorbidities (hypertension, diabetes, and hyperlipidemia), and 28 control individuals who were matched for age and sex. CIMT and PWV of the left common carotid artery were measured. At 12-month follow-up after bariatric surgery, measurements were repeated in the 38 patients with obesity.

Results Mean baseline body mass index (BMI) in the MHO group was 40.55 ± 3.59 kg/m^2, which decreased by 33.1% after bariatric surgery. Compared with controls, CIMT and PWV were increased in MHO (543.53 ± 55.29 vs. 407.82 ± 53.09 μm, 6.70 ± 1.22 vs. 5.45 ± 0.74 m/s, respectively; all $P < 0.001$). At 12 months post-bariatric surgery, CIMT in MHO was lower than baseline (466.79 ± 53.74 vs. 543.53 ± 55.29 μm, $P = 0.009$), but PWV was not significantly different from baseline (6.27 ± 0.86 vs. 6.70 ± 1.22 m/s, $P = 0.132$). Multivariate regression showed that BMI was an independent predictor of CIMT ($\beta = 0.531$, $P < 0.001$).

Conclusion Carotid artery structure and function were impaired in MHO, and improved carotid artery structure was associated with weight loss in MHO after bariatric surgery.

Keywords Obesity · Carotid intima-media thickness · Pulse-wave velocity · Bariatric surgery

Introduction

Obesity, which has become a global epidemic, places patients at a greater risk for cardiovascular morbidity and mortality by increasing blood pressure, dyslipidemia, and glucose intolerance [1]. The American Heart Association has identified obesity as an independent risk factor for cardiovascular disease (CVD) [2]. However, not all obese individuals have metabolic disorders, this condition being termed "metabolically healthy obesity" (MHO) [3, 4]. Most studies [5–7] suggest that MHO is obesity (body mass index [BMI) > 30 kg/m^2) without the presence of metabolic diseases, such as type 2 diabetes, dyslipidemia, or hypertension. However, there is great inconsistency in the definitions of MHO, with a high degree of variability surrounding the prevalence of this phenotype, which has been estimated to be between 10 and 47% depending on the criteria used [4, 8, 9]. Long-term studies have suggested that MHO is a transient state. Ten-year observational studies have reported that individuals with MHO develop metabolic syndrome (MetS) [10, 11]. An increased risk for cardiovascular events was observed in obese middle-aged men (hazard ratio 1.95, 95% confidence interval 1.14 to 3.34) without MetS, as compared with normal-weight individuals without MetS, during more than 30 years of follow-up [12].

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The guidelines state that patients with a BMI ≥ 40 kg/m^2 without coexisting medical problems or with a BMI ≥ 35 kg/m^2 and one or more severe obesity-related complications are eligible for bariatric surgery [13]. Regarding surgical types, there are sleeve gastroplasty (SG), Roux-en-Y gastric bypass (RYGB), and laparoscopic adjustable gastric band (LAGB). Bariatric surgery is the only treatment that produces sustainable weight loss and improvement in obesity-related comorbidities and quality of life among patients with extreme obesity.

Carotid intima-media thickness (CIMT) is defined as the combined thickness of the inner two layers of the carotid arteries; aortic pulse wave velocity (PWV) is a surrogate marker for atherosclerosis and CVD risk [14, 15]. Many studies indicate that carotid structure, estimated as CIMT, and arterial stiffness, estimated as PWV, are improved in obesity after bariatric surgery [16–18]. However, MHO has not received much attention in these studies, while the beneficial effect of bariatric surgery in MHO is as yet unclear. We investigated the effect of substantial weight loss following bariatric surgery on CIMT and PWV in MHO.

Methods

General information

We prospectively collected data from 275 patients who underwent sleeve gastrectomy for obesity between March 2020 and September 2023 at our institution. All patients, with BMI ≥ 40 kg/m^2 without coexisting medical problems or BMI ≥ 35 kg/m^2 and one or more severe obesity-related complications are eligible for bariatric surgery. A total of 121 patients with severe obesity were free of hypertension (systolic blood pressure [SBP] ≥ 140 mmHg and/or diastolic blood pressure [DBP] ≥ 90 mmHg), diabetes mellitus, dyslipidemia, atrial fibrillation, heart failure, or previous ischemic cardiac and cerebral events. Finally, 38 patients (34 women, four men) were included in our study 12 months after bariatric surgery. The lost to follow-up rate was 68.6%.

We also included 28 metabolically healthy normal-weight individuals, matched for age and sex. The controls were outpatients who were undergoing physical examination during the study period and who volunteered to participate in this study.

Thirty-eight participants were evaluated at baseline (pre-surgery) and 12 months after bariatric surgery (post-surgery). Anthropometry, BP measurements, metabolic changes, and ultrasound (US) examinations were performed on each occasion. The control group was evaluated only once.

Anthropometric and blood pressure measurements

Body weight, waist, abdomen circumference, and hip circumference were measured, and BMI, body surface area (BSA), and waist-hip ratio were calculated. Brachial BP was measured using a digital electronic manometer (705cp; Omron, Kyoto, Japan) with a suitable adult-sized cuff according to arm circumference after > 10-min rest.

Metabolic changes

Blood samples were taken after fasting for at least 10 h. Plasma triglycerides (TG) and total cholesterol were quantified using a commercially available enzymatic kit (Beckman Coulter biochemical analysis System, Suzhou, China). Plasma glucose was measured using the hexokinase method on a Beckman Coulter biochemical analyzer.

US assessment

Doppler US of the carotid arteries was performed by a dedicated cardiac radiologist. All measurements were taken by one of two investigators using a MyLab Twice (Esaote, Italy) US device equipped with a 4–13 MHz vascular probe (LA523) and automatic quality intima-media thickness (QIMT) and quality arterial stiffness (QAS) capability.

Two sonographers performed a standardized US examination. QIMT measurement was performed in a longitudinal section, strictly perpendicular to the US beam, with the arterial wall clearly visualized. A high-quality standard B-mode image was acquired along a section of the left common carotid artery at least 1.5 cm in length, and automatic QIMT calculation was activated, measuring the IMT in real time, using the radiofrequency reception signal (Fig. 1A).

Automatic QAS measurements were performed on the same left common carotid arterial segments as those used to measure IMT, evaluating the modification in arterial internal diameter between systolic and diastolic phases (Fig. 1B). Carotid arterial internal diameter waveforms were assessed with US and converted to carotid arterial pressure waveforms using an empirically derived exponential relationship between pressure and arterial cross-section. The derived carotid arterial pressure waveform was calibrated to brachial end-diastolic pressure and mean arterial pressure by iteratively changing the wall rigidity coefficient, allowing for calculation of arterial stiffness. The carotid stiffness index PWV (m/s) was obtained, as described previously [19]. Unlike the method used for measuring carotid-femoral (cf-PWV), we performed 'local' pulse wave tracking and PWV measurements using a radiofrequency-based ultrasound vessel-wall tracking technique to assess local elastic arterial PWV.

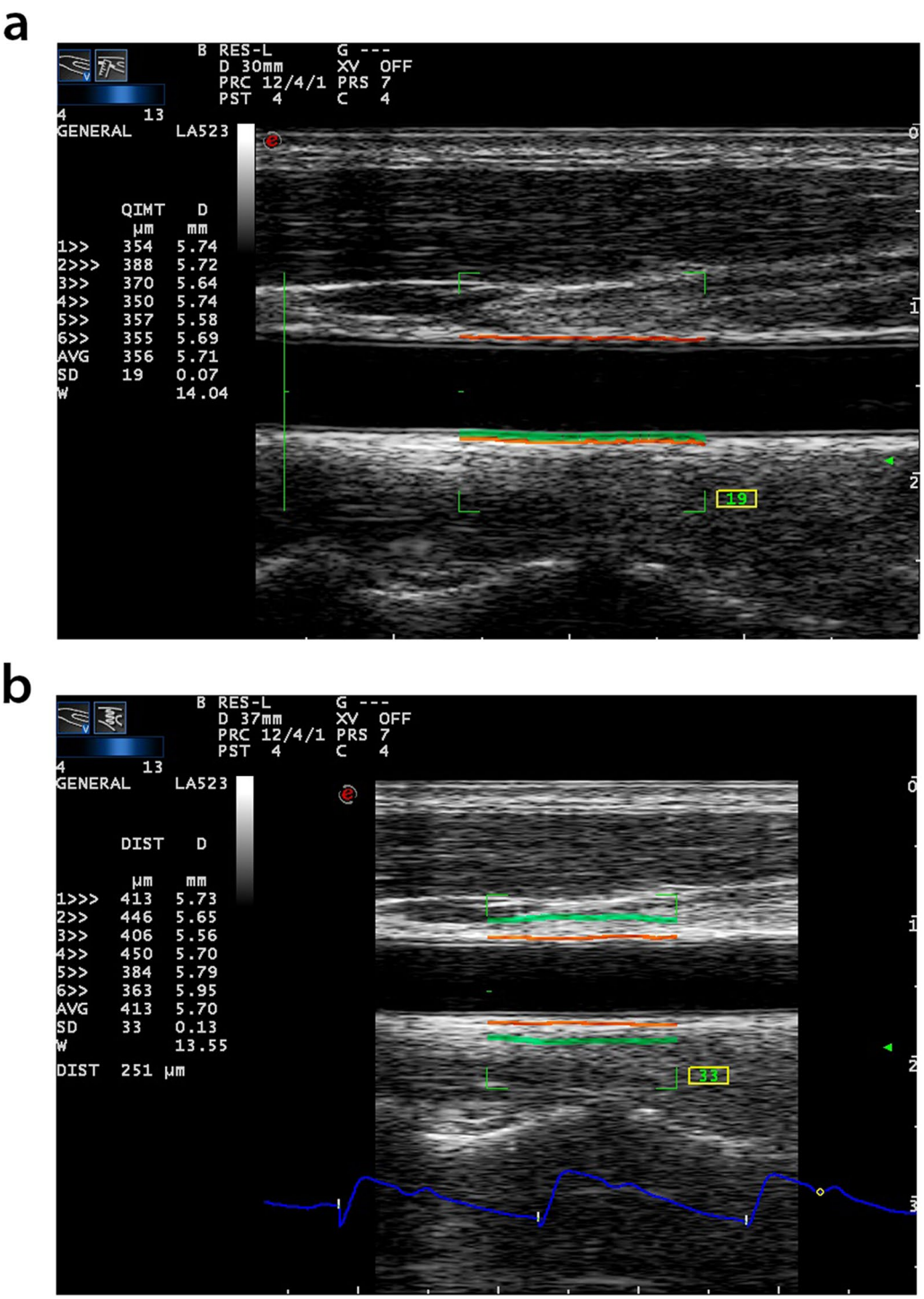

Fig. 1 Demonstration of measurement of: (**A**) left carotid artery intima-media thickness (IMT) and (**B**) Quality Arterial Stiffness (QAS). (**A**): In the two-dimensional ultrasound image, the region of interest (ROI) cursor and a vertical reference line (to left of cursor) were superimposed, as shown. The line was placed below 0.5 cm of the carotid bulb and the ROI was placed at a fixed distance of 1 cm from the line. The green line inside the ROI indicates the intima and the orange line indicates the adventitia. The data to the left of the screen comprise six successive measurements, which are computed and continuously updated by the system, showing the average (AVG) and standard deviation (SD) of IMT (left column) and vessel dimensions (**D**, right column), with the width (W) of the ROI box at the bottom. The automatic detection system, which gives real-time feedback, helps the operator to achieve the best possible measurements. (**B**) QAS automatically measured modification of arterial diameter between systolic and diastolic phases on the same arterial segment (defined by the ROI box) as used for IMT measurement. The system cyclically computes six successive measurements of both arterial distension (DIST) and diameter (**D**) (columns of data on left): their average (AVG) and standard deviation (SD) and the width of the ROI cursor are displayed. Carotid arterial stiffness indices were obtained automatically from the waveform (blue line) of arterial distension produced by real-time automatic analysis of the radiofrequency signal (Esaote MyLabTwice) after brachial blood pressure values were input by the operator

Statistical analysis

Spss20.0 software was used to analyze the experimental data. Categorical variables are presented as absolute and relative (%) frequencies; continuous variables are presented as mean ± SD (normally distributed) or as median (IQR) (for non-normally distributed variables). The rates were compared using the chi-square test. Continuous variables were compared before and after surgery using a paired *t*-test (normally distributed variables) or Wilcoxon signed rank test (non-normally distributed variables). Correlations between arterial parameters and clinical parameters were analyzed using Pearson's correlation coefficient. To investigate the relationship between carotid intima-media thickness and clinical parameters, we performed a multivariate regression analysis. A P value < 0.05 was considered statistically significant. GraphPad Prism 6.0 was used for graphing (GraphPad Software, San Diego, CA, USA).

Results

The mean age in the MHO group was 28.97 ± 6.96 years (range 22–43 years). Mean age in the control group was 31.46 ± 5.47 years (range 22–40 years). Demographic information, changes in anthropometric and metabolic parameters, and echocardiographic measurements, including CIMT and PWV in the control group and in the MHO group pre- and post-surgery, are summarized in Table 1. Baseline body weight, BMI, BSA, waist circumference, abdominal circumference, hip circumference, waist-hip ratio, SBP, DBP, and triglycerides in the MHO group were significantly higher than those in the control group (all $P < 0.001$). Additionally, baseline CIMT and PWV were significantly higher in the MHO group than in the control group (all $P < 0.001$).

After surgery, mean weight loss in the MHO group was 37.13 kg and mean BMI was significantly reduced, from 40.55 ± 3.59 kg/m^2 to 27.14 ± 3.66 kg/m^2 ($P < 0.001$). There were significant differences between pre -and post-surgery in weight, BMI, BSA, waist, abdomen, and hip circumference, and waist-hip ratio ($P < 0.001$ for all), with all values higher than those in the control group ($P < 0.001$ for all). There were no significant differences between pre- and post-surgery in SBP, DBP, and triglycerides ($P = 0.088$, $P = 0.593$, and $P = 0.311$, respectively).

Postoperative CIMT was significantly decreased (466.79 ± 53.74 μm vs. 543.53 ± 55.29 μm; $P = 0.009$) but higher than that in the control group (466.79 ± 53.74 μm vs. 407.82 ± 53.099 μm; $P < 0.001$). However, postoperative PWV was not significantly decreased (6.27 ± 0.86 vs. 6.70 ± 1.22 m/s; $P = 0.132$), and it was higher than that in the

Table 1 Comparison of demographic, anthropometric, and metabolic measurements and carotid intima-media thickness and pulse-wave velocity in the control group and the group with metabolically healthy obesity pre- and post-surgery

	Control	MHO	
		Pre-surgery	Post-surgery
Female gender, n (%)	25(89.2%)	34(89.5%)	34(89.5%)
Age (years)	31.46 ± 5.47	28.97 ± 6.96	28.97 ± 6.96
Weight (kg)	55.87 ± 5.97	112.21 ± 12.39*	75.08 ± 11.16*#
BMI (kg/m2)	21.11 ± 1.51	40.55 ± 3.59*	27.14 ± 3.66*#
BSA	1.5(1.5,1.6)	2.31(2.2,2.4)	1.8(1.7,1.9)
Waist (cm)	72.11 ± 5.23	116.13 ± 2.30*	87.74 ± 9.20*#
Abdomen circumference (cm)	77.46 ± 4.89	121.45 ± 14.69*	91.21 ± 8.37*#
Hip circumference (cm)	92.04 ± 4.86	124.50 ± 8.75*	102.21 ± 6.90*#
Waist-hip ratio	0.8(0.72,0.8)	0.9(0.9,1.0) *	0.9(0.8,0.9) *#
Systolic BP (mmHg)	108.96 ± 8.08	125.97 ± 9.21*	122.24 ± 9.14*
Diastolic BP (mmHg)	74.14 ± 5.34	82.47 ± 5.14*	80.89 ± 4.74*
HR (bpm)	76(70.25,81.5)	78(75.5,84)	76(68,80.25)
FPG (mmol/L)	4.55 ± 0.29	4.56 ± 0.46	4.61 ± 0.68
Triglyceride (mmol/L)	0.68 ± 0.19	1.27 ± 0.34*	1.19 ± 0.28*
Total-C (mmol/L)	4.17 ± 0.34	4.03 ± 0.62	4.07 ± 0.57
CIMT (μm)	407.82 ± 53.09	543.53 ± 55.29*	466.79 ± 53.74*#
PWV(m/s)	5.45 ± 0.74	6.70 ± 1.22*	6.27 ± 0.86*

MHO: metabolically healthy obesity, BMI: body mass index, BSA: body surface area, BP: blood pressure, HR: heart rate, FPG: fasting plasma glucose, total-C: total cholesterol, CIMT: carotid intima-media thickness, PWV: pulse wave velocity. *: The rates were compared using the chi-square test. Continuous variables were compared pre-surgery vs. control and post-surgery vs. control using the independent sample T test or Wilcoxon signed rank test (non-normally distributed variables). Continuous variables were compared pre- and post-surgery using a paired t-test (normally distributed variables) or Wilcoxon signed rank test (non-normally distributed variables). Compared with control group, $P < 0.05$; #: compared with pre-surgery, $P < 0.05$

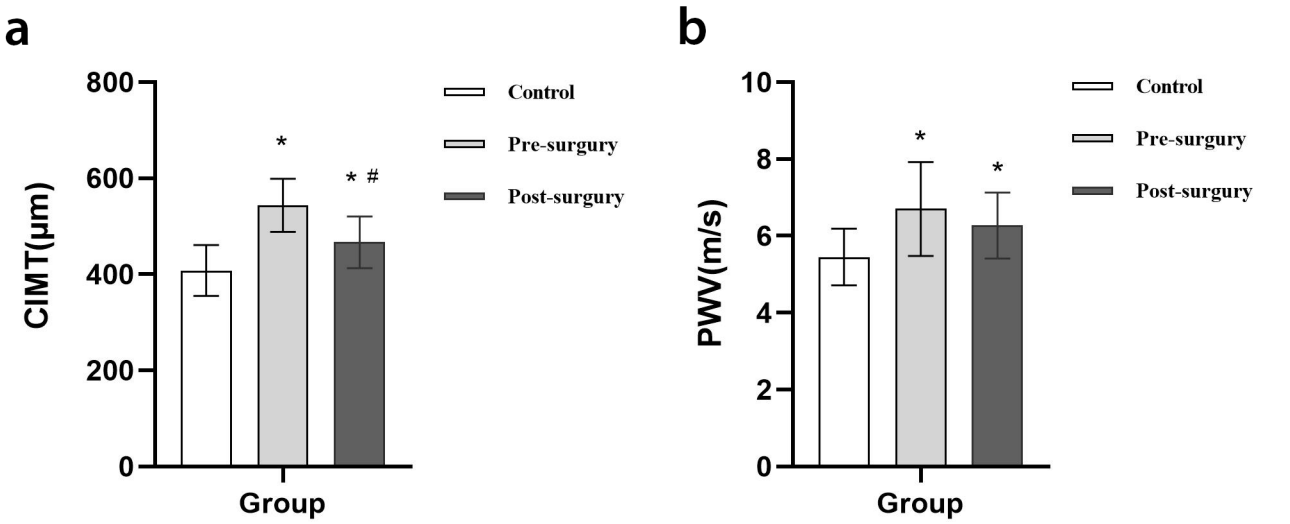

Fig. 2 Changes of carotid intima-media thickness (**A**) and PWV (**B**) before and 12 months after bariatric surgery, in the control group and the MHO group. Pre-surgury: MHO group before bariatric surgery; post-surgery: MHO group 12 months after bariatric surgery. CIMT was, respectively, 407.82 (95%CI:387.24,428.41) μm, 543.53 (95%CI:525.35,561.70) μm, and 466.79 (95%CI:449.13,484.45) μm in the control group, pre-surgery and post-surgery. PWV was, respectively, 5.45 (95%CI:5.16,5.73) m/s, 6.70 (95%CI:6.30,7.10) m/s, and 6.27 (95%CI:5.98,6.55) m/s in the control group, pre-surgery and post-surgery. *: Compared with the control group, $P<0.05$, #: Compared with pre-surgery, $P<0.05$

Table 2 Correlation analysis between carotid intima-media thickness and various clinical variables

Variables	CIMT	
	r	*P*
Weight (kg)	0.551	< 0.001
BMI (kg/m2)	0.601	< 0.001
BSA	0.513	< 0.001
Waist (cm)	0.555	< 0.001
Abdomen circumference (cm)	0.552	< 0.001
Hip circumference (cm)	0.537	< 0.001
Waist-hip ratio	0.345	< 0.001

CIMT: carotid intima-media thickness, BMI: body mass index, BSA: body surface area. Pearson's correlation coefficient was used

Table 3 Multivariate linear regression analysis of carotid intima-media thickness

Variables	CIMT	
	β	*P*
Constant		< 0.001
BMI	0.531	< 0.001
Weight	-0.473	0.198
BSA	-0.392	0.135
Waist (cm)	0.075	0.728
Abdomen circumference (cm)	0.077	0.710
Hip circumference (cm)	-0.034	0.878
Waist-hip ratio	0.018	0.876

CIMT: carotid intima-media thickness, BMI: body mass index, BSA: body surface area

control group (6.27 ± 0.86 vs. 5.45 ± 0.74 m/s; $P<0.001$) (Fig. 2).

Correlation analysis showed that CIMT was correlated with body weight, BMI, BSA, waist circumference, abdominal circumference, hip circumference, and waist-hip ratio, with significant differences ($r=0.345$–0.601, $P<0.001$ for all) (Table 2). Multivariate linear regression analysis showed that only BMI was an independent predictor of CIMT ($\beta=0.531$, $P<0.001$) (Table 3).

Discussion

In this prospective cohort study, we compared changes in CIMT and stiffness in MHO before and after bariatric surgery. We excluded participants with hypertension, diabetes, and dyslipidemia, which is a novel approach compared with that of previous studies. The results showed that CIMT was significantly decreased after bariatric surgery in MHO, but PWV did not change significantly following bariatric surgery.

Changes in carotid artery CIMT after bariatric surgery

CIMT can serve as an early marker of atherosclerosis and an independent predictor of future cardiovascular events [20, 21]. In our study, CIMT at baseline in individuals with MHO was significantly higher than that in controls, which is consistent with previous studies [22].

Bariatric surgery is the only treatment that can consistently reduce body weight and also reduce obesity-related comorbidities while improving quality of life in patients with extreme obesity. Several studies [18, 23] have observed that CIMT is significantly decreased in patients with extreme obesity after bariatric surgery. Nabavi et al. [24] reported that CIMT significantly decreased from 0.53 mm to 0.50 mm in 32 morbidly obese patients after bariatric surgery. In our study, postoperative CIMT significantly improved over baseline in the MHO group, from 543 μm to 466 μm, consistent with previous findings. Studies by Altin and Kaul [17, 25] show that significant improvement in CIMT occurs as early as 6 months after bariatric surgery, but they found no significant change from 6 months to 12 months. Lupoli suggested [18] that the rapid improvement in CIMT may be due to substantial improvement in obesity-induced proinflammatory status following bariatric surgery. One study [26] demonstrated that levels of systemic inflammatory markers C-reactive protein, interleukin 6, and tumor necrosis factor-α are significantly decreased after bariatric surgery. Jonker suggested [27] that the beneficial effects of bariatric surgery are more pronounced in younger patients.

In our study, the MHO group experienced significant weight loss after surgery, from 112.21 kg to 75.08 kg, and BMI was reduced from 40.55 kg/m^2 to 27.14 kg/m^2. Multivariate regression revealed that the reduction in CIMT was significantly associated with the reduction in BMI. Kaul [17] reported that BMI was decreased after surgery among patients with obesity, while CIMT was also significantly decreased, indicating that structural changes in the carotid artery could be reversed by weight loss, which is consistent with our findings. We can conclude that sustained weight loss after bariatric surgery slows early progression of artherosclerosis.

Several mechanisms may be involved in the improvement of CIMT after bariatric surgery. The improvement of endothelial dysfunction may be one reason for the decrease in CIMT after bariatric surgery. Whereas flow-mediated dilation (FMD) identifies abnormalities of endothelial function preceding the development of a structural lesion, CIMT indicates the presence of vascular structural damage, suggestive of a more advanced stage of atherosclerosis. Sturm et al. [28] and Lupoli et al. [18] demonstrated that endothelial dysfunction, evaluated by FMD, and CIMT-thickening were reversible via bariatric surgery-induced weight loss in obese adults. Moreover, the improvement of CIMT may be related to a substantial improvement of the obesity-related inflammatory status occurring after bariatric surgery [26].

Changes in carotid artery PWV after bariatric surgery

PWV is an objective and effective index to evaluate arterial stiffness, which is, moreover, convenient to use and practical in clinical settings [29, 30]. Increased arterial stiffness has been observed in patients with overweight or obesity in comparison with metabolically healthy normal-weight individuals [31], and even among obese pre-adolescent children [32, 33]. Our study showed that the mean PWV at baseline in the MHO group was significantly higher than that in the control group, suggesting impaired carotid artery function in MHO. Increased arterial stiffness in obese individuals has been reported to be associated with extracellular matrix remodeling, perivascular adipose tissue inflammation, and immune cell dysfunction [34].

Previous studies using PWV as an indicator to evaluate changes in arterial stiffness after bariatric surgery have produced conflicting results, including describing them as decreased [16, 35], unchanged [36], and even increased [37]. We suggest that these results may be related to differences in the study population (e.g., age, sex, race, and ethnicity), study design (type of bariatric surgery and duration of follow-up), and measurement of arterial stiffness (type of PWV). Although there are studies reporting different results, a meta-analysis of 13 trials including 1426 individuals (including those with MetS) demonstrated a remarkable decline of PWV after bariatric surgery: thus, the decrease of PWV might be utilized as an independent surrogate marker of improvement of atherosclerosis cardiovascular disease risk after bariatric surgery [38].

We found that postoperative PWV was decreased in MHO, but the difference was not statistically significant in that we did not observe significant improvement in carotid artery function. This result may be related to the fact that

the SBP and DBP were not significantly different between baseline and post-operatively in MHO. Frey [39] reported that postoperative PWV showed a moderate, non-significant decrease in the overall population; however, patients with pathological preoperative PWV (31 patients with PWV > 10 m/s and/or > 2 SD, according to age) were significantly improved after surgery (at 1, 3, and 6 months). In these patients with a high cardiovascular risk, bariatric surgery reduces arterial stiffness early. Giudici [16] observed that carotid PWV at 8 months after bariatric surgery in MHO was decreased by 23% compared with baseline, which is inconsistent with our research results. We believe that the differences in these findings are mainly due to differences in the enrolled study participants. The average BMI of patients in Giudici's study was 47.9 ± 7.1 kg/m^2, which was significantly higher than that in our study participants, and patients with hyperlipidemia were not excluded; thus, improvement in the PWV was observed earlier after surgery.

Limitations

This study has several limitations. First, because some patients were lost to follow-up, the effectiveness of long-term follow-up was poor; therefore, the sample size was limited, which restricts our classification analysis. Second, the duration of follow-up was relatively limited and no follow-up was performed more than 12 months after bariatric surgery, limiting our ability to evaluate arterial structure and function in patients who underwent bariatric surgery beyond 1 year. Future large-scale prospective studies are warranted to investigate the effect of changes in carotid artery structure and function on cardiovascular outcomes after bariatric surgery. Third, in our study, there were significantly more women than men among participants, this representing gender bias in scientific research.

Conclusions

Carotid artery structure and function are impaired in MHO. Improvement in carotid artery structure is associated with weight loss in MHO individuals after bariatric surgery. Although no significant improvement in carotid artery function is observed, MHO individuals can still benefit from bariatric surgery.

Abbreviations

MHO	Metabolically healthy obesity
MetS	Metabolic syndrome
CIMT	Carotid intima-media thickness
PWV	Pulse wave velocity
CVD	Cardiovascular diseases
BMI	Body mass index
BSA	Body surface area
Total-C	Total cholesterol
FPG	Fasting plasma glucose

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Jiping Xue, Shuai Li and Hongyu Yang. The first draft of the manuscript was written by Yanxia Zhang and Chunsong Kang. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Not applicable. This study was only primary research; further study is now in progress.

Declarations

Ethics approval This study was performed in line with the principles of the Declaration of Helsinki. This study was approved by the Ethics Committee of Shanxi Bethune Hospital.

Consent for publication Not applicable.

Consent to participate Written informed consent was obtained from all participants.

Competing interests The authors declare that they have no conflict of interest.

References

1. Safar ME, Czernichow S, Blacher J (2006) Obesity, arterial stiffness, and cardiovascular risk. J Am Soc Nephrol 17(4 Suppl 2):S109–S111. https://doi.org/10.1681/ASN.2005121321
2. Powell-Wiley TM, Poirier P, Burke LE, Després JP, Gordon-Larsen P, Lavie CJ, Lear SA, Ndumele CE, Neeland IJ, Sanders P, St-Onge MP (2021) Obesity and Cardiovascular Disease: A Scientific Statement from the American Heart Association. Circulation 143(21):e984–e1010. https://doi.org/10.1161/cir.0000000000000973
3. Hinnouho GM, Czernichow S, Dugravot A, Batty GD, Kivimaki M, Singh-Manoux A (2013) Metabolically healthy obesity and risk of mortality: does the definition of metabolic health matter? Diabetes Care 36(8):2294–2300. https://doi.org/10.2337/dc12-1654
4. Muñoz-Garach A, Cornejo-Pareja I, Tinahones FJ (2016) Does Metabolically Healthy Obes Exist? Nutrients 8(6). https://doi.org/10.3390/nu8060320
5. Blüher M (2010) The distinction of metabolically 'healthy' from 'unhealthy' obese individuals. Curr Opin Lipidol 21(1):38–43. https://doi.org/10.1097/MOL.0b013e3283346ccc
6. Blüher M (2020) Metabolically healthy obesity. Endocr Rev 41(3). https://doi.org/10.1210/endrev/bnaa004

7. Primeau V, Coderre L, Karelis AD, Brochu M, Lavoie ME, Messier V, Sladek R, Rabasa-Lhoret R (2011) Characterizing the profile of obese patients who are metabolically healthy. Int J Obes 35(7):971–981. https://doi.org/10.1038/ijo.2010.216
8. Cătoi AF, Busetto L (2019) Metabolically healthy obesity and bariatric surgery. Obes Surg 29(9):2989–3000. https://doi.org/10.1007/s11695-019-03964-8
9. Tsatsoulis A, Paschou SA (2020) Metabolically healthy obesity: Criteria, Epidemiology, controversies, and consequences. Curr Obes Rep 9(2):109–120. https://doi.org/10.1007/s13679-020-00375-0
10. Hwang YC, Hayashi T, Fujimoto WY, Kahn SE, Leonetti DL, McNeely MJ, Boyko EJ (2015) Visceral abdominal fat accumulation predicts the conversion of metabolically healthy obese subjects to an unhealthy phenotype. Int J Obes 39(9):1365–1370. https://doi.org/10.1038/ijo.2015.75
11. Soriguer F, Gutiérrez-Repiso C, Rubio-Martín E, García-Fuentes E, Almaraz MC, Colomo N, Esteva de Antonio I, de Adana MS, Chaves FJ, Morcillo S, Valdés S, Rojo-Martínez G (2013) Metabolically healthy but obese, a matter of time? Findings from the prospective Pizarra study. J Clin Endocrinol Metab 98(6):2318–2325. https://doi.org/10.1210/jc.2012-4253
12. Arnlöv J, Ingelsson E, Sundström J, Lind L (2010) Impact of body mass index and the metabolic syndrome on the risk of cardiovascular disease and death in middle-aged men. Circulation 121(2):230–236. https://doi.org/10.1161/circulationaha.109.887521
13. Mechanick JI, Apovian C, Brethauer S, Timothy Garvey W, Joffe AM, Kim J, Kushner RF, Lindquist R, Pessah-Pollack R, Seger J, Urman RD, Adams S, Cleek JB, Correa R, Figaro MK, Flanders K, Grams J, Hurley DL, Kothari S, Seger MV, Still CD (2020) Clinical practice guidelines for the Perioperative Nutrition, metabolic, and nonsurgical support of patients undergoing bariatric procedures–2019 update: Cosponsored by American Association of Clinical Endocrinologists/American College of Endocrinology, the Obesity Society, American Society for Metabolic and Bariatric Surgery, Obesity Medicine Association, and American Society of Anesthesiologists. Obes (Silver Spring Md) 28(4):O1–o58. https://doi.org/10.1002/oby.22719
14. Darabian S, Hormuz M, Latif MA, Pahlevan S, Budoff MJ (2013) The role of carotid intimal thickness testing and risk prediction in the development of coronary atherosclerosis. Curr Atheroscler Rep 15(3):306. https://doi.org/10.1007/s11883-012-0306-4
15. Valencia-Hernández CA, Lindbohm JV, Shipley MJ, Wilkinson IB, McEniery CM, Ahmadi-Abhari S, Singh-Manoux A, Kivimäki M, Brunner EJ (2022) Aortic pulse Wave Velocity as Adjunct risk marker for assessing Cardiovascular Disease Risk: prospective study. Hypertension 79(4):836–843. https://doi.org/10.1161/hypertensionaha.121.17589
16. Giudici A, Palombo C, Kozakova M, Morizzo C, Losso L, Nannipieri M, Berta R, Hughes AD, Cruickshank JK, Khir AW (2020) Weight loss after bariatric surgery significantly improves carotid and cardiac function in apparently healthy people with morbid obesity. Obes Surg 30(10):3776–3783. https://doi.org/10.1007/s11695-020-04686-y
17. Kaul A, Kumar A, Baksi A, Singla V, Aggarwal S, Gulati G, Narang R, Kashyap L (2021) Impact of bariatric surgery on carotid intima-medial thickness and cardiovascular risk: results of a prospective study. Surg Endosc 35(11):6006–6012. https://doi.org/10.1007/s00464-020-08088-0
18. Lupoli R, Di Minno MN, Guidone C, Cefalo C, Capaldo B, Riccardi G, Mingrone G (2016) Effects of bariatric surgery on markers of subclinical atherosclerosis and endothelial function: a meta-analysis of literature studies. Int J Obes 40(3):395–402. https://doi.org/10.1038/ijo.2015.187
19. Yuan LJ, Xue D, Duan YY, Cao TS, Yang HG, Zhou N (2013) Carotid arterial intima–media thickness and arterial stiffness in pre-eclampsia: analysis with a radiofrequency ultrasound technique. Ultrasound Obstet Gynecol 42(6):644–652. https://doi.org/10.1002/uog.12409
20. Chan SY, Mancini GB, Kuramoto L, Schulzer M, Frohlich J, Ignaszewski A (2003) The prognostic importance of endothelial dysfunction and carotid atheroma burden in patients with coronary artery disease. J Am Coll Cardiol 42(6):1037–1043. https://doi.org/10.1016/s0735-1097(03)00927-6
21. Van Gaal LF, Mertens IL, De Block CE (2006) Mechanisms linking obesity with cardiovascular disease. Nature 444(7121):875–880. https://doi.org/10.1038/nature05487
22. Farello G, Antenucci A, Stagi S, Mazzocchetti C, Ciocca F, Verrotti A (2018) Metabolically healthy and metabolically unhealthy obese children both have increased carotid intima-media thickness: a case control study. BMC Cardiovasc Disord 18(1):140. https://doi.org/10.1186/s12872-018-0874-5
23. Marchesi F, Giacosa R, Reggiani V, De Sario G, Tartamella F, Melani E, Mita MT, Cinieri FG, Cecchini S, Ricco M, Salcuni P, Roncoroni L (2017) Morphological changes in the Carotid Artery Intima after gastric bypass for morbid obesity. Obes Surg 27(2):357–363. https://doi.org/10.1007/s11695-016-2279-9
24. Nabavi N, Ghodsi A, Rostami R, Torshizian A, Jamialahmadi T, Jangjoo A, Nematy M, Bahari A, Ebrahimzadeh F, Mahmoudabadi E, Khadem-Rezaiyan M, Rajabzadeh F, Goshayeshi L (2022) Impact of bariatric surgery on Carotid Intima-Media thickness in patients with morbid obesity: a prospective study and review of the literature. Obes Surg 32(5):1563–1569. https://doi.org/10.1007/s11695-022-05976-3
25. Altin C, Erol V, Aydin E, Yilmaz M, Tekindal MA, Sade LE, Gulay H, Muderrisoglu H (2018) Impact of weight loss on epicardial fat and carotid intima media thickness after laparoscopic sleeve gastrectomy: a prospective study. Nutr Metab Cardiovasc Dis 28(5):501–509. https://doi.org/10.1016/j.numecd.2018.02.001
26. Askarpour M, Khani D, Sheikhi A, Ghaedi E, Alizadeh S (2019) Effect of bariatric surgery on serum inflammatory factors of obese patients: a systematic review and Meta-analysis. Obes Surg 29(8):2631–2647. https://doi.org/10.1007/s11695-019-03926-0
27. Jonker FHW, van Houten VAA, Wijngaarden LH, Klaassen RA, de Smet A, Niezen A, Schelfhout L, Bruning TA, van der Harst E (2018) Age-Related effects of bariatric surgery on early atherosclerosis and Cardiovascular Risk reduction. Obes Surg 28(4):1040–1046. https://doi.org/10.1007/s11695-017-2962-5
28. Sturm W, Tschoner A, Engl J, Kaser S, Laimer M, Ciardi C, Klaus A, Weiss H, Sandhofer A, Patsch JR, Ebenbichler CF (2009) Effect of bariatric surgery on both functional and structural measures of premature atherosclerosis. Eur Heart J 30(16):2038–2043. https://doi.org/10.1093/eurheartj/ehp211
29. Mattace-Raso FU, van der Cammen TJ, Hofman A, van Popele NM, Bos ML, Schalekamp MA, Asmar R, Reneman RS, Hoeks AP, Breteler MM, Witteman JC (2006) Arterial stiffness and risk of coronary heart disease and stroke: the Rotterdam Study. Circulation 113(5):657–663. https://doi.org/10.1161/circulationaha.105.555235
30. Sipilä K, Koivistoinen T, Moilanen L, Nieminen T, Reunanen A, Jula A, Salomaa V, Kaaja R, Kööbi T, Kukkonen-Harjula K, Majahalme S, Kähönen M (2007) Metabolic syndrome and arterial stiffness: the Health 2000 Survey. Metabolism 56(3):320–326. https://doi.org/10.1016/j.metabol.2006.10.008
31. Li P, Wang L, Liu C (2017) Overweightness, obesity and arterial stiffness in healthy subjects: a systematic review and meta-analysis of literature studies. Postgrad Med 129(2):224–230. https://doi.org/10.1080/00325481.2017.1268903
32. Cote AT, Phillips AA, Harris KC, Sandor GG, Panagiotopoulos C, Devlin AM (2015) Obesity and arterial stiffness in children: systematic review and meta-analysis. Arterioscler Thromb Vasc Biol 35(4):1038–1044. https://doi.org/10.1161/atvbaha.114.305062

33. Ruiz-Moreno MI, Vilches-Perez A, Gallardo-Escribano C, Vargas-Candela A, Lopez-Carmona MD, Pérez-Belmonte LM, Ruiz-Moreno A, Gomez-Huelgas R, Bernal-Lopez MR (2020) Metabolically healthy obesity: Presence of arterial stiffness in the Prepubescent Population. Int J Environ Res Public Health 17(19). https://doi.org/10.3390/ijerph17196995
34. Aroor AR, Jia G, Sowers JR (2018) Cellular mechanisms underlying obesity-induced arterial stiffness. Am J Physiol Regul Integr Comp Physiol 314(3):R387–r398. https://doi.org/10.1152/ajpregu.00235.2016
35. Bäckdahl J, Andersson DP, Eriksson-Hogling D, Caidahl K, Thorell A, Mileti E, Daub CO, Arner P, Rydén M (2018) Long-term improvement in aortic pulse Wave Velocity after weight loss can be predicted by White Adipose tissue factors. Am J Hypertens 31(4):450–457. https://doi.org/10.1093/ajh/hpx201
36. Streese L, Königstein K, Goricki L, Infanger D, Wölnerhanssen B, Peters T, Schmidt-Trucksäss A, Hanssen H (2019) Short- and Long-Term effects of bariatric surgery on vascular phenotype. Obes Surg 29(4):1301–1308. https://doi.org/10.1007/s11695-018-03679-2
37. Wang FM, Yang C, Tanaka H, Coresh J, Ndumele CE, Matsushita K (2021) Increase in arterial stiffness measures after bariatric surgery. Atherosclerosis 320:19–23. https://doi.org/10.1016/j.atherosclerosis.2021.01.013
38. Jamialahmadi T, Reiner Ž, Alidadi M, Kroh M, Simental-Mendia LE, Pirro M, Sahebkar A (2021) Impact of bariatric surgery on pulse Wave Velocity as a measure of arterial stiffness: a systematic review and Meta-analysis. Obes Surg 31(10):4461–4469. https://doi.org/10.1007/s11695-021-05611-7
39. Frey S, Jacobi D, Pichelin M, Cariou B, Mirallié E, Blanchard C (2020) Improvement in arterial stiffness (pOpmètre®) after bariatric surgery. Results from a prospective study. Ann Endocrinol 81(1):44–50. https://doi.org/10.1016/j.ando.2020.01.002