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Review

Cardiometabolic Syndrome: From Epidemiological Features and Pathogenesis to Surgical Treatment Strategies

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Abstract

Cardiometabolic syndrome (CMS) is a major risk factor for cardiovascular disease (CVD). It leads to increased cardiovascular and all-cause mortality. CMS is defined by the presence of abdominal obesity, hypertension, elevated triglycerides, reduced high-density lipoprotein cholesterol (HDL-C) levels, and glucose intolerance. With the increasing prevalence of metabolic diseases such as obesity and diabetes, CMS has become a significant threat to public health. As an intervention to improve the pathophysiological mechanisms of CMS, surgical treatment has achieved remarkable progress in recent years in the fields of metabolic surgery, cardiovascular reconstruction, and emerging technologies. Particularly for patients with obesity and type 2 diabetes accompanied by insulin resistance, surgical intervention can significantly improve metabolic parameters and cardiovascular outcomes. This article reviews the pathogenesis of CMS, surgical treatment approaches, and the evaluation of surgical outcomes, aiming to provide a comprehensive reference for the surgical management of CMS. By analyzing recent relevant studies, it discusses the current status and future directions of surgical treatment for CMS.

Keywords: cardiac metabolic syndrome; surgical treatment; metabolic diseases; research progress discussed

1. Introduction

Cardiac Metabolic Syndrome (CMS) is a clinical entity characterized by abdominal obesity, insulin resistance (IR), hypertension, and dyslipidemia [1]. It represents a global epidemic, affecting approximately 25% of the adult population worldwide [2]. CMS is associated with an increased risk of developing cardiovascular disease (CVD) and diabetes. It is characterized by the simultaneous presence of at least three of the following conditions: abdominal obesity, elevated plasma glucose, elevated blood pressure, elevated triglycerides (TG), or reduced high-density lipoprotein (HDL) cholesterol [3]. The additional components of CMS are interconnected through cytokines released by adipose tissue, including (1) a pro-inflammatory state, manifested by elevated C-reactive protein (CRP); and (2) a prothrombotic state, characterized by increased plasma plasminogen activator inhibitor-1 and fibrinogen [4]. Microalbuminuria, increased inflammation/oxidative stress, endothelial dysfunction, non-alcoholic steatohepatitis, abnormalities in the coagulation system, and an enhanced renin-angiotensin-aldosterone system (RAAS) in cardiovascular tissues collectively contribute to the pathophysiology of CMS [5]. The cumulative effect of these metabolic and underlying risk factors drives the development of atherosclerotic cardiovascular disease and elevates the risk of type 2 diabetes, stroke, and cognitive impairment [6,7]. It is estimated that the prevalence of metabolic syndrome in the United States is approximately 35% among adult men and women, while in the age group of 60 and above, the prevalence increases to around 50%, particularly among women [8,9]. The prevalence of CMS demonstrates a rising trend across populations in various countries, confirming the global burden of the disease [10]. Multiple prospective cohort studies and meta-analyses have demonstrated that CMS is associated with an increased relative risk of cardiovascular events (twofold increase), diabetes (3.5 to 5-fold increase), and all-cause mortality (1.5-fold increase) [11]. In a longitudinal cohort study involving one million Chinese individuals, the prevalence of cardiometabolic multimorbidity increased from 2.41% to 5.94% over a 5-year period, indicating a growing severity of cardiometabolic diseases [12].

Although lifestyle interventions (such as dietary modifications and increased physical activity) serve as the cornerstone treatment for CMS, many patients struggle to achieve sustained weight loss and metabolic improvements through these approaches. While pharmacological therapies have made some progress in recent years, their efficacy remains suboptimal and is often accompanied by side effects and limitations [13]. Consequently, surgical treatment has garnered increasing attention as an effective alternative intervention. Surgical treatment plays a critical role in the management of CMS, particularly for patients with obesity and metabolic disorders. Metabolic surgeries (such as gas-

tric bypass and sleeve gastrectomy) not only lead to significant weight loss but also improve insulin resistance, reduce blood pressure, and decrease the risk of cardiovascular diseases [14]. Studies have shown that metabolic surgery can achieve long-term remission of type 2 diabetes, reduce the use of antihypertensive medications, and improve cardiovascular outcomes [15]. However, despite demonstrating significant efficacy in the management of CMS, surgical treatment still presents certain limitations and challenges. Issues such as surgical risks, the sustainability of long-term outcomes, and the selection of appropriate surgical indications remain subjects of further investigation and discussion. In the future, with advancements in technology and ongoing research, surgical treatment will play an increasingly important role in the management of CMS. Subsequently, this article will provide a detailed elaboration on the pathogenesis of CMS, surgical treatment approaches, and outcome evaluation, aiming to offer a comprehensive reference for the surgical management of CMS.

2. Epidemiology

The global prevalence of CMS is rising rapidly. According to the 2023 Global Report on Metabolic Diseases, the adult prevalence rate of CMS has reached 25%–30%, with the obesity and diabetes epidemics being the primary driving factors. According to the latest data from China, the prevalence of CMS among adults aged $\geq$18 years is 24.5%, and it is positively correlated with the incidence of coronary heart disease, heart failure, and stroke [16].

3. Pathological Mechanisms

The pathogenesis of CMS is complex and involves multiple systems and organs. Research indicates that obesity is a key risk factor for CMS, as it promotes the development and progression of the condition by adversely affecting insulin sensitivity, inflammatory responses, and other pathways [17]. In individuals with obesity, dysfunctional adipose tissue secretes various pro-inflammatory cytokines, such as tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6). These factors contribute to insulin resistance, which subsequently triggers metabolic disorders and exacerbates vascular endothelial injury. Furthermore, hypertension and dyslipidemia are also recognized as significant pathogenic factors in CMS. Both conditions can damage vascular endothelial cells, promote the development of atherosclerosis, and increase the risk of cardiovascular diseases [17,18]. Additionally, hepatic metabolic dysfunction and myocardial energy metabolism remodeling are also critical contributors to the pathogenesis of CMS. Hepatic metabolic dysregulation leads to increased gluconeogenesis and overproduction of very-low-density lipoprotein (VLDL), resulting in hypertriglyceridemia. Meanwhile, myocardial energy metabolism remodeling enhances fatty acid oxidation while reducing glucose utilization, ultimately impairing cardiac contractile efficiency [19].

The pathological mechanisms in patients with CMS complicated by diabetes are more complex, involving a series of interconnected pathways. The pathological mechanisms in patients with comorbid diabetes are more complex, involving a series of interrelated pathways. Under hyperglycemic conditions, excessive glucose influx into cells triggers mitochondrial superoxide production, consequently exacerbating oxidative stress [20]. This is considered the primary initiating cause of diabetes-induced organ damage [20]. Increased production of reactive oxygen species (ROS) induces tissue damage through multiple mechanisms, including activation of the polyol and hexosamine pathways—thereby exacerbating oxidative stress in a vicious cycle—activation of protein kinase C (PKC), non-enzymatic glycation of proteins leading to the formation of advanced glycation end products (AGEs), and upregulation of their cellular receptor RAGE [21]. In turn, AGEs can directly damage the heart, blood vessels, and kidneys. They promote cross-linking of matrix proteins, increasing tissue stiffness. Thus, AGEs are intricately involved in the pathogenesis of diabetes-related organ damage, including conditions such as diabetic cardiomyopathy and atherosclerosis. Both AGEs and ROS are also closely associated with endothelial dysfunction, which is a critical factor in the development of both microvascular and macrovascular complications in diabetes [22]. Furthermore, hyperglycemia is associated with activation of the local renin-angiotensin-aldosterone system (RAAS) in myocardial tissue. This activation of RAAS exerts multiple adverse effects on both organs, promoting vasoconstriction, fibrosis, and the deterioration of organ dysfunction [11].

4. Surgical Treatment

4.1 Cardiovascular Surgery and Interventional Therapy

Surgical interventions for cardiovascular complications play a critical role in the management of CMS. These primarily include coronary artery bypass grafting (CABG), transcatheter aortic valve replacement (TAVR), percutaneous coronary intervention (PCI), left ventricular reduction surgery, and cardiac resynchronization therapy. These procedures can effectively improve cardiac function and alleviate symptoms. However, they are associated with certain limitations, such as high procedural risks and prolonged recovery periods.

4.1.1 Coronary Artery Bypass Grafting (CABG)

CABG is the primary treatment for multivessel coronary artery disease and remains one of the most common cardiac surgeries performed worldwide [23]. CABG is associated with a low mortality rate and improves coronary revascularization and cardiac function [24]. The procedure involves using the patient's own blood vessels, such as the internal mammary artery and saphenous vein, as grafts to bypass narrowed or blocked coronary arteries, thereby restoring blood supply to the heart muscle. Studies have

demonstrated that CABG significantly alleviates symptoms and improves quality of life in patients. Meta-analyses of previous randomized controlled trials (RCTs) indicate that while CABG demonstrates long-term advantages in terms of repeat revascularization, target vessel revascularization, and non-operative myocardial infarction, it is associated with an increased risk of early stroke (at 30 days and 1 year) and perioperative myocardial infarction [25]. The findings from Gallo *et al*. [26] demonstrate that percutaneous coronary intervention is associated with a significantly higher risk of myocardial infarction within 5 years compared to CABG, which undoubtedly represents a critical factor in treatment decision-making for patients with left main disease. The aforementioned studies collectively demonstrate the superiority of CABG in treating coronary artery disease. However, the procedure is still associated with certain limitations, such as its invasive nature, prolonged postoperative recovery period, and risks of cognitive decline and increased incidence of depression, which may adversely affect quality of life and the ability to perform activities of daily living (ADLs) [27].

4.1.2 Percutaneous Coronary Intervention (PCI)

PCI has advanced remarkably as a modality for revascularization in patients with focal severe coronary artery disease. This progress has been driven by the advent of newer-generation drug-eluting stents, calcium modification techniques, state-of-the-art intravascular imaging, invasive physiology, and ventricular assist devices [28]. The procedure involves inserting a catheter into the coronary artery and deploying a stent to expand the narrowed vessel, thereby restoring blood flow. It offers significant benefits, including restoration of cardiac blood perfusion, improvement of clinical symptoms, prevention of disease progression, and reduction in short-term mortality [29]. However, some patients continue to experience adverse cardiovascular events after PCI despite receiving conventional secondary preventive therapy. Previous studies have indicated that the incidence of such post-PCI adverse cardiovascular events—including procedure-related myocardial infarction, repeat revascularization, and all-cause mortality—ranges from approximately 5% to 15% [30]. Furthermore, related research has shown that the recurrence rate of chest pain can be as high as 50% [31]. These adverse events pose significant threats to patient health and survival and lead to increased healthcare expenditures due to higher rates of rehospitalization.

4.1.3 Transcatheter Aortic Valve Replacement (TAVR)

TAVR is a minimally invasive surgical procedure used to treat aortic valve stenosis. In 1989, Danish cardiologist Henning Rud Andersen performed the first animal implantation of what is now known as TAVR, which received official authorization in 1995. The first human TAVR procedure was performed on a 57-year-old male in 2002, marking the beginning of a new interventional era. Subsequently, the Society of Thoracic Surgeons established a standardized scoring tool to calculate the risk associated with aortic valve replacement surgery. In 2011, the U.S. Food and Drug Administration (FDA) granted approval for the Edwards SAPIEN transcatheter aortic valve replacement (TAVR) system for use in patients with severe aortic stenosis who were deemed inoperable or not suitable for open-heart surgery [32]. TAVR is an effective treatment for severe valvular heart disease. This procedure involves delivering a prosthetic valve via catheter to the aortic valve site to replace the diseased valve and restore normal cardiac function. TAVR is particularly suitable for elderly patients and those at high surgical risk, offering advantages such as minimal invasiveness and rapid recovery. However, the procedure still carries significant risks, including postoperative bleeding and infective endocarditis [33].

4.1.4 Left Ventricular Reduction Surgery and Cardiac Resynchronization Therapy (CRT)

For patients with end-stage heart failure and significant ventricular dilation, the treatment strategy of performing ventricular reduction surgery (partial resection of dilated myocardial tissue) to improve cardiac pumping efficiency has, in recent years, seen its clinical role diminish due to emerging limitations in benefits. Its application status has now been superseded by cardiac device implantation therapy. Multiple studies have confirmed that left ventricular reduction surgery significantly improves cardiac function and clinical outcomes in patients with ischemic cardiomyopathy. Based on Laplace's law (which states that reducing left ventricular volume decreases wall stress, thereby enhancing systolic function), Patrick *et al*. [34] demonstrated that the hybrid ventricular reconstruction procedure using the Revivent TC system achieved comparable or even superior improvements in functional and echocardiographic parameters. Researchers from the team of Tulner [35,36] at Leiden University Medical Center provided scientific validation for left ventricular reconstruction surgery through pressure-volume analysis (using the conductance catheter method as the gold standard). Their work confirmed that this surgical approach improves systolic/diastolic function, reduces wall stress, corrects mechanical dyssynchrony, and enhances mechanical efficiency [34]. Cardiac resynchronization therapy (CRT) is an established treatment for patients with refractory, mild to severe systolic heart failure, impaired left ventricular function, and prolonged QRS duration. Although classified as a non-surgical intervention, it requires surgical device implantation. Studies have demonstrated that CRT can improve left ventricular ejection fraction (LVEF) by 15% to 20% at six months after the procedure [37].

4.2 Metabolic Surgery

Metabolic surgery significantly improves blood glucose, blood pressure, and lipid profiles in patients with obesity and comorbid CMS by altering the anatomical structure of the digestive tract. The primary procedures include Roux-en-Y gastric bypass (RYGB) and sleeve gastrectomy (SG).

4.2.1 Roux-en-Y Gastric Bypass Surgery

Roux-en-Y Gastric Bypass (RYGB), as the most commonly performed and effective bariatric procedure, not only leads to significant weight loss but also induces remission of type 2 diabetes (T2DM) [38]. Extensive research has demonstrated that improved insulin sensitivity and restored pancreatic beta-cell function, manifested as enhanced glucose-stimulated insulin secretion, represent the core mechanisms underlying these benefits. Furthermore, increased glucose utilization and modulation of gut hormone secretion play pivotal roles in sustaining the long-term metabolic efficacy of the procedure. Numerous studies have focused on alterations in circulating gut hormone levels following RYGB. Although some findings appear contradictory, the overall consensus indicates that due to the direct connection of the stomach to the distal small intestine, hormones primarily secreted by enteroendocrine cells (EECs) in the lower gut—such as glucagon-like peptide-1 (GLP-1), oxyntomodulin, cholecystokinin (CCK), and secretin—are significantly increased. In contrast, ghrelin (derived from the gastric remnant) and glucose-dependent insulinotropic polypeptide (GIP, secreted by K cells in the bypassed duodenum) are likely reduced [39–41]. Previous studies have observed elevated postprandial peptide YY (PYY) levels in both RYGB rat models and human subjects [41]. In human patients, RYGB surgery results in an increased number of PYY and GLP-1-positive cells along both the alimentary limb and the biliopancreatic limb [42]. The sustained elevation in GLP-1 levels is believed to mediate metabolic benefits by inhibiting gastric motility, inducing satiety, suppressing glucagon secretion, and stimulating insulin release. Recent studies have further proposed that the increased secretion of PYY—which is co-secreted with GLP-1 from hypothalamic L-cells—is equally important. PYY (1–36) is cleaved by dipeptidyl peptidase-4 to form PYY (3–36), which induces satiety through central mechanisms. In contrast, although intact PYY (1–36) does not affect food intake, it stimulates beta-cell proliferation and promotes their quiescence. Notably, PYY is also abundantly present in pancreatic islets, where it may exert an underappreciated local paracrine regulatory role. Alterations in insulin, glucagon, and somatostatin produced by pancreatic endocrine cells also contribute to the remission of T2DM. Following Roux-en-Y gastric bypass (RYGB), fasting insulin levels can decrease by up to 60% due to improved insulin sensitivity and enhanced clearance. Previous laboratory studies have indicated that PYY and GLP-1 can be adaptively expressed in pancreatic islets under conditions of cellular stress. In humans following RYGB, intestinal GIP mRNA levels are reduced, while the density of GIP-positive cells paradoxically increases [34]. In conclusion, these adaptive alterations in gut hormones play an essential role in cellular stress adaptation.

4.2.2 Sleeve Gastrectomy

Compared to other bariatric procedures, sleeve gastrectomy offers multiple advantages, including technical simplicity, the absence of anastomotic requirements, suitability as a bridging intervention for high-risk patients, low rates of major complications (0.2%–10%), and low mortality (<1%). Furthermore, it demonstrates a shorter learning curve compared to RYGB [43]. Owing to these advantages, sleeve gastrectomy has emerged as the preferred bariatric procedure for morbidly obese patients worldwide and has become the most frequently performed weight loss surgery over the past decade [44]. Sleeve gastrectomy demonstrates comparable efficacy to Roux-en-Y gastric bypass (RYGB) in treating obesity and related comorbidities in both the short and long term, with patients maintaining good quality of life [45]. Furthermore, the procedure is technically less demanding than other malabsorptive procedures [46]. Sleeve gastrectomy involves longitudinal resection of the gastric fundus and proximal antrum along the lesser curvature, resulting in a tubular digestive pathway while maintaining gastrointestinal continuity [44]. Its mechanisms are mediated through multiple effects including restricted food intake, early satiation, reduced ghrelin secretion, and increased secretion of glucagon-like peptide-1 (GLP-1) and peptide YY-36 (PYY-36) [47,48]. Recent meta-analyses have demonstrated that laparoscopic sleeve gastrectomy (LSG) achieves an average excess weight loss (EWL) of 57.6% at 1 year and 70.1% at 3 years postoperatively. The procedure's key advantages include relative technical simplicity, no requirement for anastomosis, preservation of gastrointestinal integrity, minimal risks of ulceration and internal herniation, low incidence of dumping syndrome, significant reduction in ghrelin levels, and substantial improvement in quality of life [42]. At specialized centers, the overall complication rate is below 15%, with an in-hospital mortality of approximately 0.3% [49]. It is noteworthy that the incidence of early staple-line complications (such as bleeding and leakage) can reach up to 6%. These complications not only increase mortality risk but also lead to significant rises in hospitalization costs and resource utilization [50]. Similar to all bariatric procedures, sleeve gastrectomy is not exempt from long-term complications. The primary long-term side effect of sleeve gastrectomy is gastroesophageal reflux disease (GERD). Recent studies indicate that the proportion of patients developing GERD symptoms following sleeve gastrectomy ranges from 20% to 60% [51].

5. Emerging Surgical Techniques

The core of Cardiometabolic Syndrome (CMS) lies in the confluence of metabolic disorders (obesity, insulin resistance, hypertension, dyslipidemia) and elevated cardiovascular risk. Traditional management has primarily relied on pharmacological and surgical interventions, yet their efficacy remains limited for severe cases. In recent years, the rapid advancement of minimally invasive and precision-based surgical techniques has provided new directions for the management of CMS. Several emerging surgical techniques, such as Renal Denervation (RDN) and Percutaneous Intramyocardial Septal Radiofrequency Ablation (PIMSRA), demonstrate potential for application in the management of Cardiometabolic Syndrome (CMS).

5.1 Renal Denervation (RDN)

Renal autonomic innervation is composed of both sympathetic and parasympathetic components, which form the renal plexus. Blood pressure regulation depends on afferent nerves that modulate sympathetic outflow and efferent nerves that regulate the renal renin-angiotensin-aldosterone system. RDN (Renal Denervation) is an innovative minimally invasive interventional technique. The procedure involves first positioning a catheter within the renal artery. This catheter is then used to deliver either radiofrequency thermal energy or ultrasound waves to ablate the superficial sympathetic nerves surrounding the artery, while ensuring the renal artery itself remains undamaged. This process reduces systemic sympathetic tone, leading to a decrease in blood pressure, and is indicated for the treatment of resistant hypertension [52]. Several studies have indicated that blocking sympathetic nerve activity may represent a viable therapeutic target for hypertension treatment [53,54]. The clinical consensus from the European Society of Cardiology (ESC) has demonstrated the safety and efficacy of Renal Denervation (RDN) both in the presence and absence of antihypertensive medications [55]. Long-term data further support its durability, with the SPYRAL HTN-ON MED trial demonstrating sustained blood pressure reduction in patients taking antihypertensive medications. Additionally, the SPYRAL HTN-OFF MED study showed a 14 mmHg reduction in systolic blood pressure ($p < 0.01$) at 6 months post-procedure, along with mild improvements in glycemic control and insulin sensitivity [56]. Another study has indicated that Renal Denervation (RDN) is a safe and effective strategy for modulating autonomic nervous system activity. Beyond its blood pressure-lowering effects, RDN has also demonstrated favorable electrophysiological changes, reverse remodeling, and potential antiarrhythmic effects in animal models of atrial fibrillation [53]. Compared to previous surgical approaches, the aforementioned studies suggest that patients with CMS and comorbid resistant hypertension may derive greater benefit from Renal Denervation (RDN) therapy.

5.2 Percutaneous Intramyocardial Septal Radiofrequency Ablation (PIMSRA)

Percutaneous Intramyocardial Septal Radiofrequency Ablation (PIMSRA) is a therapeutic approach for managing patients with drug-refractory hypertrophic obstructive cardiomyopathy (HOCM). Under ultrasound guidance, a radiofrequency ablation needle is percutaneously inserted through the intercostal space toward the cardiac apex. The application of radiofrequency energy generates localized high temperatures to ablate the hypertrophied ventricular septum, thereby alleviating patient symptoms [57]. PIMSRA has been demonstrated to exhibit high safety and efficacy in treating hypertrophic obstructive cardiomyopathy (HOCM). This procedure offers multiple advantages including no requirement for sternotomy, avoidance of cardiopulmonary bypass, short access path, minimal invasiveness, and rapid postoperative recovery [58]. Multiple studies have demonstrated that PIMSRA reduces hypertrophic septal volume through a minimally invasive approach, directly alleviating cardiac hemodynamic abnormalities in patients with hypertrophic obstructive cardiomyopathy (HOCM). This is particularly significant for patients with comorbid CMS, as improved cardiac output enhances systemic organ perfusion, thereby indirectly ameliorating metabolic status [59,60]. Although current research specifically targeting the Cardiometabolic Syndrome (CMS) population remains limited, existing literature and clinical experience suggest that Percutaneous Intramyocardial Septal Radiofrequency Ablation (PIMSRA) holds significant clinical implications for CMS management: (1) Cardiac structure and function improvement: Directly alleviates cardiovascular complications associated with CMS; (2) Synergistic amelioration of metabolic disorders: Indirectly modulates the pathological underpinnings of CMS; (3) Minimally invasive advantages: Reduces perioperative risks in CMS patients. These technical advancements enhance procedural precision and safety, thereby opening novel therapeutic avenues for CMS treatment.

6. Efficacy Evaluation of Surgical Treatment

Evaluation of surgical treatment outcomes constitutes a critical component in the management of Cardiometabolic Syndrome (CMS). Current commonly employed assessment methods include cardiac function evaluation and metabolic parameter monitoring. Through comprehensive evaluation of surgical outcomes, timely adjustments to treatment strategies can be made to enhance therapeutic efficacy.

6.1 Cardiac Function Assessment

Cardiac function assessment serves as a critical metric for evaluating surgical outcomes. Commonly employed modalities include echocardiography and cardiac magnetic resonance imaging (MRI). These techniques enable comprehensive evaluation of both systolic and diastolic cardiac

performance, thereby elucidating the improvements in cardiac function achieved through surgical intervention.

6.2 Metabolic Monitoring

Monitoring of metabolic parameters serves as an essential approach for evaluating the improvement of metabolic disorders following surgical intervention. Key metabolic indicators include blood glucose and lipid profiles, insulin sensitivity, among others. Tracking changes in these parameters enables quantitative assessment of the procedure's efficacy in ameliorating metabolic dysregulation.

6.3 Quality of Life Assessment

Quality of life assessment constitutes a vital aspect of evaluating surgical treatment outcomes. Commonly utilized methods include standardized questionnaires and patient self-reporting measures. By assessing patients' QoL, clinicians can gauge the impact of surgical interventions on daily living, thereby facilitating further optimization of treatment strategies.

7. Challenges in Surgical Treatment

While surgical treatment has brought revolutionary breakthroughs to CMS management, its clinical application still faces multiple challenges. Firstly, the refinement of precise indication stratification requires urgent advancement: current bariatric surgery guidelines recommending BMI cut-off values are primarily based on European and American population data. For Asian populations frequently presenting with "normal-weight metabolic abnormality" (NWMA, characterized by BMI <25 kg/m^2 with visceral adiposity), the benefits of surgery remain undefined. There is a pressing need to develop individualized assessment systems centered on insulin resistance index (HOMA-IR ≥ 2.9) and adiponectin levels (<4 µg/mL). Secondly, controversies persist regarding long-term efficacy sustainability and complication management: metabolic surgery demonstrates 30%–40% weight recurrence rates at 5-year follow-up, with diabetes relapse being closely linked to gut microbiota dysbiosis and decreased GLP-1 receptor sensitivity [61]. Following cardiovascular reconstruction surgery, the graft vessel disease progression rate increases at an annual rate of 5%–7%. CMS patients with comorbid chronic kidney disease face a 2.3-fold higher risk of postoperative acute kidney injury [62], highlighting the need to establish genetic polymorphism-based postoperative monitoring models. Furthermore, standardized protocols for multidisciplinary collaboration have not been fully established: technical details requiring coordination include preoperative identification of pulmonary hypertension by anesthesiology departments (NT-proBNP >300 pg/mL with tricuspid regurgitation velocity >2.8 m/s), intraoperative precise glycemic control (target range 6–10 mmol/L), surgical procedure selection, and postoperative metabolic management by endocrinology departments. Consensus on these multimodal approaches remains to be established through multicenter registry studies [63]. Looking ahead, with advances in precision medicine, personalized surgical decision-making models incorporating metabolomic profiling and comprehensive anesthesiologic evaluation hold promise for optimizing therapeutic strategies. Concurrently, the application of novel biomaterials and ongoing innovations in minimally invasive techniques are anticipated to further enhance perioperative safety and comprehensive patient benefits.

8. Conclusion

Cardiometabolic Syndrome (CMS) is a systemic disorder driven by the pathophysiological interactions among metabolic abnormalities, chronic kidney disease (CKD), and cardiovascular disease (CVD). Surgical intervention plays a critical role in the comprehensive management of CMS, particularly for patients with obesity and type 2 diabetes accompanied by insulin resistance. Operative approaches can significantly improve metabolic parameters and cardiovascular outcomes in this population. The surgical management of Cardiometabolic Syndrome (CMS) has evolved beyond mere weight reduction and revascularization to multi-target metabolic modulation. The synergistic application of metabolic and cardiovascular surgeries offers novel pathways for improving patient outcomes. Although surgical intervention plays a significant role in alleviating symptoms and enhancing prognoses in CMS, it is accompanied by certain limitations and challenges. Primarily, these procedures carry inherent risks, particularly for elderly patients with multiple comorbidities. Secondly, the long-term efficacy of surgical treatments requires further investigation and validation. Additionally, the substantial costs associated with surgical interventions may limit their accessibility in some regions. Therefore, strict adherence to indications and contraindications is essential to optimize therapeutic efficacy and quality of life for patients. Looking ahead, continued advancements in medical technology and research will lead to more precise and effective surgical treatments for Cardiometabolic Syndrome (CMS). The application of novel surgical techniques is expected to enhance both the safety and efficacy of these procedures, offering renewed hope for patients. However, there are very few studies focusing directly on emerging technologies for the CMS population, and further clinical trials are needed to substantiate their clinical value. Currently, standardized multidisciplinary protocols have not been fully established, and there is no literature outlining a unified treatment strategy. Multicenter registry studies remain necessary to build consensus. In the future, with advances in medical science, the integrated multidisciplinary treatment model is expected to establish standardized protocols. Consequently, surgical interventions for CMS are anticipated to become increasingly targeted and effective, thereby bringing greater hope to patients.

Abbreviations

CMS, cardiac metabolic syndrome; CKD, chronic kidney disease; CVD, cardiovascular disease; TG, triglycerides; HDL, high-density lipoprotein; CRP, c-reactive protein; RAAS, renin-angiotensin-aldosterone system; TNF-α, tumor necrosis factor-alpha; IL-6, interleukin-6; PKC, protein kinase c; AGE, advanced glycation end products; CABG, coronary artery bypass grafting; RYGB, Roux-en-Y gastric bypass; EECs, endocrine cells; GLP-1, glucagon-like peptide-1; CCK, cholecystokinin; PYY, peptide YY; TAVR, transcatheter aortic valve replacement; PCI, percutaneous coronary intervention; LVEF, left ventricular ejection fraction; RDN, renal artery denervation; CEA, carotid endarterectomy; CAS, carotid artery stenting.

Author Contributions

JJ, HW, XL, ZZ and JZ conceived the initial concept of the manuscript. JJ and HW drafted the manuscript. JZ and ZZ participated in the study design and critically reviewed parts of the important intellectual content. XL critically revised the manuscript for important intellectual content. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work. All authors read and approved the final manuscript.

Ethics Approval and Consent to Participate

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Conflict of Interest

The authors declare no conflict of interest.

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