Review

Surgical ventricular restoration for patients with heart failure

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DOI:10.31083/j.rcm2204140

Submitted: 27 September 2021 Revised: 24 October 2021 Accepted: 28 October 2021 Published: 22 December 2021

On an annual basis, heart failure affects millions of people globally. Despite improvements in medications and percutaneous interventions, heart failure secondary to ischemic cardiomyopathy remains an important health issue. A large proportion of healthcare budgets are also dedicated to complications related to ischemic cardiomyopathy and heart failure. Drugs and mechanical devices have an ever-expanding role in our management of this growing patient population. However, cardiac transplantation continues to be the gold standard for treating advanced heart failure. Since there is a limited pool of suitable donor hearts, cardiac transplantation is not a viable option for many patients. Over the past five decades, various forms of surgical ventricular restoration have been proposed as an appealing option for treating heart failure in very select and specific cases. Given the pathophysiology of ischemic cardiomyopathy, literature suggests that, in those particular settings, reasonable results can be achieved by surgically restoring the ventricle to its original geometry. Herein, we explore the evidence on different operative techniques for ventricular restoration. We also present the latest findings for surgical ventricular restoration in patients with ischemic cardiomyopathy.

Keywords

Ischemic cardiomyopathy; Surgical ventricular restoration; Dor procedure; Clinical outcomes

1. Introduction

Heart failure (HF) is a major clinical and healthcare issue. In 2017, it was estimated that 65 million people suffered from HF globally [1]. The total cost of care for HF was estimated at $43 billion in the US in 2020 [2]. This cost to the healthcare system is projected to reach $70 billion by 2030 [2]. Over the past four decades various classes of heart failure medications have been introduced and used clinically. Although these therapeutics have greatly improved outcomes for patients suffering from HF, their efficacy is not universal. Indeed, the only definitive treatment for advanced heart failure is orthotopic cardiac transplant. However, there continues to be a shortage of donor hearts. Surgical management of HF has also witnessed major changes over the past three decades. After the establishment of the cardiopulmonary bypass machine, cardiac surgeons and medical engineers believed the invention of a total artificial heart would be next frontier. Early iterations did not produce promising results, so surgeons scaled back the clinical application of mechanical devices to extracorporeal membrane oxygenation, single or biventricular assist devices, and percutaneous heart pumps. These devices are not without shortcomings, which has emphasized the need to further augment current medical and non-medical management strategies. Research and development dollars should result in medications with improved safety and efficacy profiles. Newer generations of mechanical circulatory support devices will also have fewer complications. However, concurrent with these efforts, clinicians and surgeons must strive to employ strategies that have shown long-term benefits for patients suffering from HF.

Ischemic coronary artery disease (CAD) can lead to ischemic cardiomyopathy. HF can develop in the setting of persistent and significant interruption of perfusion secondary to CAD. In such cases the physiologic geometry of the heart can change, resulting in compromised cardiac function and HF. Over the years it has been posited that restoring the original shape and volume of the heart may be associated with clinical benefits in select patients suffering from HF. Collectively known as surgical ventricular restoration (SVR), various techniques have been used to achieve optimal hemodynamic and clinical outcomes in specific HF patient groups. However, it is yet to be determined whether such strategies can produce consistent results. Herein, we present the historical evolution of SVR techniques. We also outline the operative steps of SVR. Next, we summarize the clinical outcomes of SVR while paying close attention to the Surgical Treatment for Ischemic Heart Failure (STICH) Trial. Finally, we present the factors that have been associated with poor outcomes and SVR.

2. Pathophysiology of ischemia-induced ventricular remodelling

Myocardial infarction results in myocyte death in the endocardium and myocardium [3]. Emergent revascularization restores perfusion for the epicardium. However, the inner and mid layers of the myocardium are at risk of necrosis if recovery of myocardial blood flow is delayed or compromised. Such a mechanism results in the myocardium retaining its thickness and becoming akinetic, which lead to geometric changes including left ventricular (LV) remodelling. These changes result in an alteration of the three-dimensional structure of the myocardium and are characterized by LV wall thinning, increased LV volume, more LV sphericity, and decreased LV function. The common endpoint of these anatomic changes is HF [4, 5]. Importantly, in addition to gross LV remodelling, post-ischemic changes also occur at the cellular, biochemical, and metabolic level. Parameters that have been found to drive ischemia-induced LV remodelling include infarct size, infarct location, transmurality, pre- and after-load conditions, previous infarcts, and timing of revascularization [5]. To summarize, post-infarct LV remodelling entails the following changes: (i) non-contractile myocardium; (ii) increasing scar in the ischemic zone; and (iii) increased volume load. It is important to emphasize that additional infarcts can further compound remodeling.

The increases in volume load lead to a decrease in ejection fraction (EF) [6]. As an early compensatory mechanism, the LV dilates to sustain cardiac output. This dilation is an adaptive response that promotes survival. However, the long-term effects of LV dilatation are disadvantageous. Dilatation exacerbates wall tension, which is directly related to the radius and pressure within the ventricular chamber and inversely correlated to wall thickness. A higher LV volume means increased stress on the myocyte, which affects effective contraction. Moreover, increased wall stress results in more oxygen consumption, decreased subendocardial blood flow, and reduced systolic shortening. These deleterious changes impact LV function, which can manifest in cardiogenic shock acutely or may result in HF later. Furthermore, a more spheric LV can result in mitral regurgitation (MR). In fact, MR and LV dilatation can have a synergistically negative association. Mitral regurgitation results in LV dilation, which changes ventricular shape, a phenomenon that can worsen MR.

As noted above, ischemia-induced LV remodelling also has a biochemical and neurohormonal etiology. Remodeling can be driven by neurohumoral activation, which is associated with higher plasma levels of norepinephrine, angiotensin, renin, and b-type natriuretic peptide [7]. Indeed, once the ventricular volume increases beyond a threshold and its geometry is significantly compromised, HF progresses independently of neurohumoral activation [8]. Moreover, post-infarct LV remodelling can lead to HF through changes in the conduction system, where delays in interventricular conduction result in dyssynchrony between the two ventricles [9].

Ischemia-induced LV remodelling leading to HF set the foundation for surgical ventricular restoration, which aims to reduce LV volume and re-establish its geometry.

3. Surgical ventricular restoration: goal and evolution

As detailed above, changes in LV geometry due to ischemia-induced dilation contribute to the pathogenesis of ischemic cardiomyopathy. Importantly, contractility is not improved by revascularization. Indeed, to attenuate progression to HF from post-infarct LV remodelling, all corrective factors must be considered, including revascularization, valve repair, and biventricular electrical re-synchronization. SVR is an operation that is intended to reverse the pathologic changes of post-infarction LV remodelling. Simply, the objective of SVR is to restore a physiologic volume and configuration to the LV, which should decrease myocardial stress and improve cardiac function. It should be noted that SVR aims to reflect the cardiac anatomy described by Torrent-Guasp, which is defined as the helical ventricular myocardial band (HVMB) [10]. HVMB explains why the heart's narrowing, shortening, lengthening, widening, twisting, and untwisting occurs. In addition to LV reconstruction, SVR can include complete revascularization, surgery for arrythmias, and mitral valve repair (MVr), if needed.

Like many cardiac surgical operations, techniques for SVR were first explored after the establishment of the cardiopulmonary bypass machine. In principle, SVR aims to prevent ischemic cardiomyopathy through correcting the adverse remodelling that occur post-infarction. Early pioneers included Cooley, Jatene, Fontan, and Guilmet [11–14]. Most of the initial work focused on the surgical correction of ventricular aneurysms. Today, the most common SVR technique is based on the work done by Vincent Dor [15]. As opposed to Cooley's linear suture [16], and the external circular suture employed by Jatene [12], Dor used a circular patch to reconstruct the LV [15, 17]. Dor's Procedure is also known as an "endoventricular circular patch plasty" or EVCPP. His method was also originally conceived for patients with post-infarct dilated cardiomyopathy. Dor was also the first to explore the application of ventricular reconstruction in patients without aneurysmal disease. This strategy was based on considering both the akinetic and dyskinetic areas of the ventricle as aneurysmal. Therefore, both regions were accounted for when he performed coronary artery bypass graft (CABG) surgery in patients with HF [18]. In 2001, Dor presented the 17-year outcomes of his procedure, which had produced excellent hemodynamic results [19].

Dor's procedure has been refined over the years. In order to offer a more uniform ventricular remodeling operation, Menicanti introduced the use of a plastic model to guide the SVR [20]. Menicanti also developed an intraventricular strategy to repair the mitral valve [21]. Over the years, other groups have explored alternative approaches to SVR. Methods initially evolved from linear repair without the use of an intra-ventricular patch to the use of a patch, which has been associated with improved outcomes [22–24]. Further modifications shifted emphasis from LV volume reduction to restoring an ellipsoid shape for the LV [23–25]. As it was reported for the first time, Cirillo's method (dubbed the "KISS procedure") resulted in the recovery of ventricular torsion after the procedure [25, 26]. To exclude non-contracting segments in the dilated remodeled ventricle after an anterior MI, Athanasuleas [27] described the surgical anterior ventricular endocardial restoration (SAVER) procedure. More recent iterations of SVR have been based on altering the design of the intra-ventricular patch that is used to exclude the infarcted zone of the LV [28, 29].

Essentially, SVR strategies strive to return the LV to a spherical shape and size by decreasing the volume in the anterior and septal segments of the LV through the exclusion of akinetic and dyskinetic areas. Although each of these surgical approaches have produced varying levels of success [30–32], none has been adopted as an established method that has been used consistently in the clinical setting. As more long-term data from large, multi-centre cohort studies becomes available, a stronger emphasis should be placed on defining an SVR operation that can be standardized and used in the appropriate patient population.

4. The appropriate candidate for surgical ventricular restoration

A recent expert statement from the American Association of Thoracic Surgery outlines guidelines for which patients should be considered for SVR [33]. Since the conception of the Dor Procedure, surgeons believe patients with an anterior infarct, a large akinetic or dyskinetic segments and presenting with HF can be considered for SVR. Revascularization should be considered in patients who have a reasonable RV function and have retained basilar and lateral cardiac function. The gold standard imaging modality for selecting candidates for SVR is cardiac magnetic resonance. SVR may not yield optimal outcomes in patients with pulmonary hypertension and those without basilar heart function, multiple infarcted areas, and diffuse coronary artery disease that is not amenable to surgical revascularization. It is important to note that preoperative pulmonary hypertension may exacerbate right ventricular failure post-SVR [34].

Although useful as a set of guiding parameters, the above indications and contraindications should be contextualized. For instance, some groups have found that SVR may help patients with severe LV dysfunction, multi-territory infarcts, and pulmonary hypertension [35–38]. Regardless of the location of an infarct, a sufficient amount of viable myocardium is required to ensure favourable outcomes [39]. Finally, although pulmonary hypertension is considered a relative contraindication, post-SVR LV improvement can reduce the load on pulmonary vasculature and reduce resistance and pressure [37].

5. Operative approach for surgical ventricular restoration

As noted above, techniques for SVR have evolved since its inception. Here, we describe an approach that has been commonly reported in the literature (an illustrative depiction can be found here [40]). Surgical ventricular restoration is usually performed through a conventional full median sternotomy. It is usually done concomitant with bypass surgery. Conventional cannulation and myocardial protection strategies are used. Bicaval cannulation is recommended if MVr or replacement is required. The LV may be vented via the right superior pulmonary vein or the root. Cardiopulmonary bypass is instituted, and the heart is arrested. Subsequently, CABG is performed. If indicated, the next step is MVr or replacement. In cases of recurrent ventricular arrythmias, cryoablation can also be applied to the scarred tissue of the LV at this stage. Next step is SVR.

The LV is vented, and with it collapsed, the scarred area may be apparent. As it can happen, the lack of ventricular collapse should not contraindicate SVR. Through the scarred segment, an incision is made into the anterior wall of the LV. The incision is extended to the apex and proximally parallel to the course of the left anterior descending artery. The LV is inspected and a thrombectomy is done, if indicated, followed by careful irrigation of the LV. In situations where a significant thrombus burden is present in the LV, before opening the ventricle, a left atriotomy can be helpful.

While inspecting the LV and the infarcted area, the surgeon may also be able to palpate and discern the transition zone between infarcted and non-infarcted myocardium. Next step involves excluding the dyskinetic or akinetic area of LV free wall. This is followed by the application of an endoventricular circular suture that is passed through the fibrous tissue above the transitional zone. A Dacron (polyester; Invista, Wichita, KS) patch lined with pericardium is sewn at the junction of the endocardial muscle and scarred tissue. This results in the exclusion of the non-contractile segments of the LV and septum. The excluded tissue, which is scar, is folded over the patch to aid in hemostasis. At this stage, a sizing apparatus is utilized to help reconstruct the LV. Dor introduced the use of such a device to avoid excessive resection, therefore selecting the appropriate sizing device is of paramount importance. The apparatus is placed in the LV and situated on the mitral valve annulus, thus revealing the location of the new apex. The apparatus is chosen to achieve a volume of 50–70 cc/m^2 body surface area, with 60 cc/m^2 selected for most patients. Those with a high body mass index (BMI) will have the volume decreased to 50 cc/m^2, and those with a low BMI will have the volume increased to 70 cc/m^2.

Although not commonly used anymore, a purse string suture, referred to as "the Fontan stich", can be applied to delineate the limits of the new anterior wall. The Fontan stitch starts from the new apex and is run cephalad across the septum using the anterior margin of the LV sizing device as a guide. Regardless of the amount of scarred tissue that is left behind, no more than one half of the septum should be included. Alternatively, the surgeon can use a marker to highlight the endocardium with the apparatus filled and then deflating it while the sutures are being applied. The suture is run across the anterior wall and down the lateral wall to the new apex. It is recommended to take deep partial thickness bites into the scarred area. Borders of the new distal anterior wall become apparent once the purse string is secured. It is important to keep the sizing device inflated as the purse string is being tied. Only in cases where a small SVR is needed should the purse string be tied to close the ventriculotomy. Otherwise, this should be avoided as it can result in the suture being pulled through the endocardium. This may be particularly the case in settings where a scarred tissue is not present.

The anterior wall can be constructed using a patch of Dacron that is oval-shaped and trimmed to adequately close the defect. The patch sutures are applied around the anterior purse string. The sizer is usually kept in situ until 50% of the patch is sewn. It is subsequently deflated and removed. To de-air, the LV vent is turned off. The suture lines are inspected for hemostasis. If a small residual defect persists, a linear closure can be done superficial to the patch or purse string. Buttressed with bovine pericardium, horizontal mattress sutures are often utilized for closing the first layer. When there is well-defined scar tissue, pericardial strips are not used. A continuous running stitch of polypropylene can be used for the second layer. A series of anterior purse string sutures can be used to close the ventricular defect in cases where the defect is moderate in size, but not large enough for further patching. This should be done before applying the mattress sutures.

As mentioned above, SVR has been adopted by many surgeons who have made modifications to the operation. Although this has provided alternative approaches, it has also resulted in a lack of a standardized procedure, which has rendered comparing outcomes difficult. McCarthy reported a no-patch, double purse-string suture strategy [41]; Mickleborough suggested a tailored scar excision, with septoplasty for a dyskinetic septum when indicated, and a modified linear closure [42]; Batista pioneered partial left ventriculectomy (PLV) [43]; Suma introduced the use of a longitudinal patch to exclude the septum and partial anterior wall as the Septal Anterior Ventricular Exclusion (SAVE) procedure, also known as the Pacopexy procedure [44]; Yaku presented endocardial linear infarct exclusion [45]; Cirillo described a procedure that entailed keeping fibers' orientation with strip patch reshaping in order to realign residual myocardial fibers in a physiologic configuration (also known as the "KISS procedure") [26]; and Menicanti proposed an approach that is similar to Dor's procedure except he employed a pre-shaped device or mannequin (TRISVR TM, Chase Medical Richardson, TX, USA) [20]. The mannequin can be beneficial in cases where the LV is not significantly enlarged. This can lessen the risk of having a critically small LV. Furthermore, it can be helpful in situations where the area between scarred and non-scarred tissue is not clear, such as in dilated cardiomyopathy and a recent infarct. The device is removed prior to closing the LV. Closure of the LV is achieved with a direct suture if it is smaller than 3 cm, or with an elliptical, synthetic patch if it is larger than 3 cm. Importantly, the device can facilitate the correct positioning of the new apex and preventing the LV from becoming a sphere. As is particularly the case for a novice surgeon, the reconstruction of the apex can be difficult when the apical and inferior regions are severely dilated. To overcome this difficulty, Menicanti suggested plication of the distal inferior wall before patch placement, hence placing the apex in a more anterior position [20, 46].

Furthermore, SVR can be performed for either anterior or posterior remodelling. Although more studies are warranted, Garatti *et al.* [47] found that patients presenting with posterior remodeling showed worse clinical signs of angina and HF and a higher proportion of moderate to severe MR. However, early- and long-term outcomes after SVR seemed to be unaffected by remodeling location [47]. More facile surgeons may elect to perform a SVR without arresting the heart for the following reasons. Various strategies have been suggested for beating heart SVR [48, 49]. A beating heart operation should reduce the risk of inflicting more ischemia-induced injury to an already poorly functioning heart [50]. Furthermore, a beating heart SVR can provide a more accurate assessment of the degree of MR pre- and post-repair/replacement. In some cases, a beating heart procedure can also better delineate the transition zone, as determined by identifying contracting and non-contracting segments of the myocardium. In contrast, performing SVR on a beating heart can be a more challenging operation. Maintaining the sizer on the mitral annulus while applying sutures is less trivial. Although this can be partially mitigated by using a pen to mark the borders of the device on the endocardium and then deflating it. There is a paucity of data comparing the outcomes of beating vs arrested heart SVR, although one study found a beating heart approach did not provide an advantage [51].

6. The mitral valve and surgical ventricular restoration

The optimal timing and technique for repairing or replacing the mitral valve during SVR is not known. Generally, when indicated, the mitral valve is attended to before performing the SVR. Menicanti *et al.* [21] have described an intraventricular repair, which is done via the ventriculotomy prior to doing the SVR. Conte and colleagues performed a reduction posterior annuloplasty through a standard interatrial groove incision before completing the SVR. This was done to reduce the risk of disrupting the closure of the LV [52]. With respect to outcomes, evidence suggests that adding mitral repair to SVR with or without CABG, or to CABG alone, increases the surgical risk [53–56]. In fact, operative mortality is approximately 16% in patients with mild-moderate MR who undergo MVr and SVR [55]. Even though MR was mild in most of the patients studied by Sartipy, overall survival was lower in those who received a combination operation compared to those who underwent isolated SVR [55].

A recent study by Hobbs and colleagues also assessed the long-term survival and durability of mitral valve procedures in patients undergoing SVR [57]. The study included 109 patients who underwent SVR between 1992 and 2017. Thirty-seven percent of the patients had concomitant MVr and 5% had SVR combined with mitral valve replacement (MVR). The study confirmed the benefits of SVR as there was a significant improvement in EF. Importantly, MVr yielded sustained improvement in MR. However, the study failed to show any changes in pre- versus post-operative MR in patients who did not receive a mitral procedure. Median follow-up was 7 years, while overall 5-, 10-, and 15-year survival rates were 72%, 48%, 26%, respectively.

More recently, Castelvecchio and colleagues investigated the early- and mid-term outcomes of patients who underwent SVR and MVr [58]. They reported 14% operative mortality, where independent predictors of early mortality were age, creatinine, EF score, prior stroke, unstable angina, and diffuse remodelling. The actuarial survival rate of the whole patient population at 3-, 5-, and 8-years was 72, 65 and 45%, respectively. Risk factors for late mortality were preoperative creatinine, previous implantation of cardioverter defibrillator, while the absence of angina at the time of surgery was a protective factor.

Various studies have shown that SVR can potentially improve mitral valve function by reducing LV volumes and papillary muscles distances and restoring a more normal heart geometry [20, 56, 59, 60]. In one study, mid-term survival, including mortality, was 93% at 1 year and 88% at 3 years [60]. This is indeed higher than what is expected in patients with post-infarct dilated LV and reduced function, which implies that the combination of MVr and SVR may not be needed in those patients. Multi-centre studies that include larger patient populations and longer follow-up periods are warranted to better understand the fate of these patients.

It is important to also note a few fundamental studies that have considered mitral valve surgery in the setting of ischemic MR. In a randomized study, Acker and colleagues compared MVr to chordal-sparing MVR in patients with severe ischemic MR [61, 62]. The study found no significant difference in LV reverse remodeling or survival at 12 months. Although MVR provided a more durable correction of MR, there was no significant difference with respect to clinical outcomes [61]. At 2-year follow-up, there was still no difference between the groups in LV reverse remodelling or survival [63]. Notably, MVr resulted in higher recurrence rates of MR, leading in more HF-related adverse events cardiovascular admissions. In another study Smith *et al.* [64] considered CABG alone or CABG combined with MVr in patients with moderate ischemic MR. At 1-year, the study found no difference in survival or LV end-systolic volume index. While concomitant MVr was associated with lower rates of recurrent moderate or severe MR, it did lead to more adverse events. The 2-year follow-up study also failed to demonstrate a survival benefit or a reduction in LV reverse remodelling in the combined group [65]. In fact, a combined procedure resulted in early risk of increased neurological events and arrythmias. Finally, Kron and colleagues [66] proposed using baseline echocardiographic parameters and clinical characteristics to predict which patients were more likely to develop recurrent MR after MVR for severe ischemic MR. The authors used logistic regression and found the major reason for recurrent MR was mitral valve leaflet tethering. The model included age, BMI, sex, race, effective regurgitant orifice area, basal aneurysm/dyskinesis, New York Heart Association (NYHA) classification, and history of CABG, percutaneous coronary intervention (PCI), or ventricular arrhythmias. Although the model provided reasonable discrimination, the authors cautioned it required validation. Other groups have also proposed the use of validated prediction models as ancillary tools that can be used to help surgeons in recommending customized and personalized treatment strategies that can optimize clinical outcomes [67].

7. Clinical outcomes of surgical ventricular restoration

Given his pioneering work on SVR, it is apt that Vincent Dor is also among the first to report consistent results for the operation [68–70]. Dor and his colleagues showed that his SVR strategy resulted in improvements in LV function, NYHA functional class, and survival. Importantly, they demonstrated such findings in patients with dilated ischemic cardiomyopathy, severe LV dysfunction, and those with classic dyskinetic aneurysms. In a large series of 245 patients, Di Donato demonstrated the surgical outcomes of the Dor Procedure correlated with the extent of LV aneurysms [71]. This study found that the mortality varied from 12.2 % and 12.5% in large LV aneurysms compared to 4.8% and 0% in small LV aneurysms, while overall mortality was 6.8% in the first 562 consecutive patients of Dor experience [71]. This study is foundational as it provides evidence that LV akinesis vs. LV dyskinesis may not significantly affect Dor Procedure outcomes. Di Donato also showed the safety and efficacy of SVR in unstable patients with a recent anterior MI [72].

The safety and efficacy of SVR was further corroborated from an international registry, the RESTORE Group (Reconstructive Endoventricular Surgery, returning Torsion Original Radius Elliptical shape to the left ventricle) [73, 74]. The study included 198 patients who had an SVR operation between 1998 and 2003. Akinesia was present in 66% of the cases and up to 73.3% in those with LV end-systolic volume (LVESV) $\geq$80 mL/m^2. The authors found a significant improvement in EF and a decrease in LV end-systolic volume index (LVESVI). Post-SVR 30-day mortality was 5.3%, where the value was higher for patients who had underwent SVR combined with MVr (8.7%). In patients who did not receive an MVr, 30-day mortality was 4.0%. Encouragingly, the overall 5-year survival was 68.6 $\pm$ 2.8%. Also, at 5 years, 78% of the cohort did not require hospitalization for HF.

In another study, Suma and colleagues reported the 7-year outcomes of SVR combined with mitral valve procedures in patients with end-stage HF [75]. This study included 246 patients who underwent left ventriculoplasty for post-infarction LV dysfunction. All patients had suffered from dyspnea with a NYHA classification of III or IV. Twenty-six patients required inotropic support before their surgery. All patients had MR of more than 2+ while 46 patients had 3+ or more MR. Mitral reconstruction (61 repairs, 15 replacements) and left ventriculoplasty was performed in combination with CABG. Importantly, three different techniques were used for SVR: the Dor Procedure, Septal Anterior Ventricular Exclusion (SAVE Procedure, also known as Pacopexy Procedure), and partial left ventriculectomy (PLV). Operative mortality was 7.9%. The EF and cardiac index increased, while the end-diastolic volume index (EDVI) and end-systolic volume index (ESVI) and diastolic dimension decreased. Late deaths were noted in 13 patients, but 1- and 5-year survival was 80.2% and 67.7%, respectively. Although the average NYHA classification improved, multivariate analysis found MR of 3+ or more and increased end-systolic volume index significantly predicted death. Age, preoperative inotropes, and pulmonary hypertension were not found to be important contributors.

Sartipy and colleagues also reported 10-year outcomes for their adoption of the Dor Procedure [76]. In their study 101 patients underwent SVR, where LV aneurysm was present in 97 of them. Bypass surgery was performed in 99 patients and 29 patients underwent intervention on their mitral valve. Early mortality was 7.9%, while mean follow-up in operative survivors was 4.4 $\pm$ 2.8 years. Actuarial survival at 1-, 3- and 5-years was 88, 79, and 65%, respectively. Another study on SVR reported a lower in-hospital mortality rate of 2.8% [42]. In this study, the 1-, 5-, and 10-year survivals were 92%, 82%, and 62%, respectively. It should be noted that the authors of this study employed the Mickleborough approach to perform SVR. Furthermore, the group considered severe MR a relative contraindication, and only 6 patients had mitral valve surgery. Surgeons at the Cleveland Clinic have also presented excellent outcomes for SVR [77]. In this study, 220 consecutive patients underwent SVR, where 17% of them had an implantable cardioverter-defibrillator (ICD) placed preoperatively, 49% had mitral valve surgery, and 7% required an intra-aortic balloon pump (IABP) postoperatively. The 30-day mortality was 1% and survival at 1-, 3-, and 5-years was 92%, 90%, and 80%, respectively. Comparing these outcomes to those of previous studies is not trivial. The authors did not report the extent or type of LV dysfunction (akinesia vs dyskinesia). Furthermore, in a retrospective study Williams *et al.* [78] showed that patients with NYHA IV who underwent SVR had similar improvements in cardiac function with acceptable, although decreased survival after SVR when compared with those with less severe clinical disease. There are also studies that have shown the safety and feasibility of SVR alone and in conjunction with CABG [79, 80].

In 2007, Menicanti, a trainee of Dor, presented the outcomes of the largest single-center study of surgical anterior restoration (1161 patients) showing a 30-day cardiac mortality of 4.7% [81]. This study also confirmed that SVR concomitant with mitral valve surgery have a significantly higher operative mortality rate compared to those undergoing isolated SVR (13% vs 3%, respectively). Importantly, subgroup analysis showed that MR alone does not significantly increase operative mortality risk. However, when MR is associated with NYHA class III or IV, the risk of mortality increases substantially. Moreover, for the first time, the study provided evidence that severe diastolic dysfunction can increase the risk of SVR. Another study presented the 6-month outcomes of 9 patients with ischemic dilated cardiomyopathy who underwent SVR with additional restrictive mitral annuloplasty and/or CABG [28]. In this study all patients were alive and had clinical improvement in NYHA classification. Cardiac output, stroke volume, and EF improved in all patients, while LV surgical remodelling was sustained at 6-months. Although a small sample size and with a short follow-up period, this study suggests that ventricular remodelling can be sustained at 6-months in patients who have received SVR combined with coronary surgery and mitral procedures.

More recently, Cui reported the 10-year outcomes of the Pacopexy SVR Procedure [82]. This was a study of 92 patients with LV aneurysm, where 57 underwent a Dor Procedure and 35 received a Pacopexy operation. The early-mortality rate was 4% for both groups. Ten-year survival was 70.4 $\pm$ 7.9% for those who had received a Pacopexy operation and 41.7 $\pm$ 7.2% patients who had undergone a Dor procedure. Freedom from re-hospitalization for HF or cardiac death was 60.0 $\pm$ 8.6% vs 28.8 $\pm$ 6.8%, for the Pacopexy and Dor groups, respectively. The study concluded that Dor procedure and LVESVI $\geq$60 mL/m^2 were significantly linked with long-term death and hospitalization for heart failure. The outcomes of Cirillo's SVR approach (the "KISS procedure") are also worth noting [25]. Twenty-nine consecutive patients with previous anterior MI and HF symptoms CABG and the SVR. The authors reported an in-hospital mortality rate of 0%, while there was a significant increase in EF and decrease in LV reverse remodelling. Importantly, increase in LV torsion was maintained at 4-year follow-up.

In another recent study, Stefanelli evaluated the short- and long-term outcomes of 62 patients with ischemic cardiomyopathy who underwent a SVR [83]. The authors identified risk factors that were associated with worse outcomes. Fifty-seven patients received CABG and MVr was done for 39 patients. Operative strategy included classic Dor operation or a technique that reduced the equatorial diameter of the LV but did not involve using a patch. Thirty-six patients died during follow-up (median follow-up of 7.02 years), where 15 deaths were from cardiac causes. Advanced age, pre-surgical IABP, reduction less than 35% of postoperative LV EDVI and ESVI, choice of surgical approach, and EF less than 25% were found

Table 1. Summary of major clinical trials that have reported outcomes of SVR (adapted from [40]).

Year	Author	Title	Number of patients and follow-up	Findings
2001	Athanasuleas [27]	Surgical anterior ventricular endocardial restoration (SAVER) in the dilated remodeled ventricle after anterior myocardial infarction	Sample size: 439 Follow-up: 18 months	Hospital mortality for the SAVER procedure was 6.6% with an 18-month survival of 89.2%.
2004	Mickleborough [42]	Left ventricular reconstruction: Early and late results	Sample size: 285 Follow-up: mean 63 $\pm$ 48 months	The modified linear closure technique resulted in an 82% survival at 5 years and a 62% survival at 10 years.
2004	Athanasuleas [73]	Surgical ventricular restoration in the treatment of congestive heart failure due to post-infarction ventricular dilation	Sample size: 1198 Follow-up: 5 years	Risk factors reported for mortality were age, preoperative EF, NYHA classification and LVESVI.
2004	Di Donato [72]	Safety and Efficacy of Surgical Ventricular Restoration in Unstable Patients With Recent Anterior Myocardial Infarction	Sample size: 74 Follow-up: Mean follow-up 40 $\pm$ 15 months	Strongly correlated with NYHA, clinical HF severity and advanced age ($>$70).
2005	The RESTORE Group [74]	Surgical Ventricular Restoration: The RESTORE Group Experience	Sample size: 1198 Follow-up: 5 years	Risk factors for death anytime after SVR were a high NHYA class, LVESI $>$80, a preop EF of $<$30 and age $>$75
2005	Sartipy [76]	The Dor procedure for left ventricular reconstruction. Ten-year clinical experience	Sample size: 101 Follow-up: Mean follow-up in operative survivors 4.4 $\pm$ 2.8 (0.1–10.4) years	The EVCPP survival at 1 year was 88% and at 5 years was 65%.
2006	Adams [38]	Does Preoperative Ejection Fraction Predict Operative Mortality With Left Ventricular Restoration?	Sample size: 89 Follow-up: 5 years	Operative mortality for both patients with preop EFs of less or greater than 25% was 3.4%, so see a benefit of SVR in low EF patients
2006	Sartipy [114]	Risk factors for mortality and hospital re-admission after surgical ventricular restoration	Sample size: 136 Follow-up: 1, 3, 5, 9 years (median 4.2 years)	The 9 year survival in those that underwent the Dor procedure was 62%.
2007	Williams [78]	Outcomes Following Surgical Ventricular Restoration for Patients With Clinically Advanced Congestive Heart Failure (New York Heart Association Class IV)	Sample size: 78 Follow-up: 32 months	Severity of NYHA class was not a significant predictor of survival. Both patients with NYHA IV and those with classifications of II-III had similar survival at 32 months.

Table 1. Continued.

Year	Author	Title	Number of patients and follow-up	Findings
2010	Yoon [67]	Decision support in surgical management of ischemic cardiomyopathy	Sample size: 1468 Follow-up: 1, 5, and 9 years	Mortality was not significantly different between those who underwent CABG alone compared to CABG with SVR.
2010	Nardi [80]	Long-term outcomes after surgical ventricular restoration and coronary artery bypass grafting in patients with postinfarction left ventricular anterior aneurysm	Sample size: 104 Follow-up: 75 $\pm$ 36 months	The mortality between SVR with multiple CABG for Multivessel CAD (MVCAD) compared to SVR +/- CABG for single vessel (LAD) was not different at 12 years follow up.
2010	Di Donato [108]	End-systolic volume following surgical ventricular reconstruction impacts survival in patients with ischaemic dilated cardiomyopathy	Sample size: 216 Follow-up: Median 38 months	An LVESVI $>$60 mL/m^2 was a strong predictor of mortality at 5 years follow up. A postoperative LVESVI of $>$60 mL/m^2 translated into a 30% probability of death at 5 years.
2011	Dor [101]	Favorable effects of left ventricular reconstruction in patients excluded from the Surgical Treatments for Ischemic Heart Failure (STICH) trial	Sample size: 274 Follow-up: 1, 3 years	The 8-year survival of the Dor procedure was 80%, even in severe HF.
2011	Witkowski [102]	Surgical Ventricular Restoration for Patients With Ischemic Heart Failure: Determinants of Two-Year Survival	Sample size: 79 Follow-up: 6 months, 2 years (median 2.7 years)	A higher preoperative NYHA class and a postoperative LVESVI of $>$60 mL/m^2 were both associated with an increased mortality at 2 years as well as worse outcomes overall.
2011	Skelley [104]	The Impact of Volume Reduction on Early and Long-Term Outcomes in Surgical Ventricular Restoration for Severe Heart Failure	Sample size: 87 Follow-up: 1 year (median 683 days)	The ideal preoperative LVESVI may be between 80 and 120 mL/m^2, as this range most often correlates with a postoperative LVESVI reduction of 30% to a volume of $<$90 mL/m^2.
2011	Isomura [105]	Volume reduction rate by surgical ventricular restoration determines late outcome in ischaemic cardiomyopathy	Sample size: 90 Follow-up: Every 6–12 months for 8 years	A reported 82.4% survival if SVR achieves a 33% reduction and postoperative ESVI $<$90 mL/m^2. However, a 100% late mortality at 8 years if reduction was less than 15% and postoperative ESVI $>$90 mL/m^2.
2012	Wang [50]	Early results after surgical treatment of left Ventricular Aneurysm	Sample size: 62 Follow-up: 0–24 months	No significant survival differences were found between linear repair and circular patch plasty.
2018	Piña [84]	Sex Difference in Patients with Ischemic Heart Failure Undergoing Surgical Revascularization: Results from the STICH Trial (Surgical Treatment For Ischemic Heart Failure)	Sample size: 1212 Follow-up: Median 9.8 years	Study using the STICH cohort. Patient sex was shown not to be a significant factor in postoperative clinical outcomes for those undergoing CABG alone.

Table 1. Continued.

Year	Author	Title	Number of patients and follow-up	Findings
2018	Wakasa [107]	Estimating postoperative left ventricular volume: Identification of responders to surgical ventricular reconstruction	Sample size: 293 Follow-up: 3, 5, 10 years (median 6.8)	Postoperative EF is significantly associated with improved survival in those with a postoperative ESVI between 40–80 mL/m^2.
2020	Cui [82]	The Pacopexy procedure for left ventricular aneurysm: a 10-year clinical experience	Sample size: 92 Follow-up: Mean follow-up of operative survivors 10.6 $\pm$ 0.7 years	LVESVI $\geq$60 mL/m^2, advanced age $\geq$65 years and the Dor procedure (when compared to Pacopexy) were significantly associated with re-hospitalization for heart failure symptoms and cardiac death
2021	Castelvecchio [116]	Comparable Outcomes Between Genders in Patients Undergoing Surgical Ventricular Reconstruction for Ischaemic Heart Failure	Sample size: 648 (STICH) Follow-up: Median 9.8 years	Long term patient outcomes not significantly different between mean and women when undergoing CABG with SVR.

to contribute to cardiac mortality long-term. Interestingly, perioperative levosimendan and preoperative moderate to severe MR affected early and intermediate term outcomes but were not statistically significant for long-term outcomes. Finally, in a STICH follow-up study, Pina *et al.* [84] found that sex is not associated with the effect of CABG and medical therapy versus medical therapy alone on all-cause mortality, cardiovascular mortality, the composite of death or cardiovascular hospitalization, or surgical deaths in patients with ischemic LV dysfunction. To compare surgical approaches adequately and accurately it is important to have prospectively designed studies that employ different SVR techniques that have been standardized. These studies should enrol the appropriate patient population and, ideally, have long-term follow-up data. Table 1 (adapted from [40]) summarizes the major studies that have reported clinical outcomes of SVR.

8. The Surgical Treatment for Ischemic Heart Failure (STICH) trial and surgical ventricular restoration

In the context of SVR, it is important to highlight the Surgical Treatment for Ischemic Heart Failure (STICH) Trial [85]. To date, this landmark study remains the largest and one of the most important and provocative trials in cardiac surgery. The trial had two main hypotheses. Hypothesis One was aimed to assess the survival benefit of CABG combined with optimal medical therapy versus medical therapy alone in patients with CAD, congestive heart failure (CHF), and LV dysfunction. Hypothesis Two was conceived to compare CABG alone to CABG combined with SVR [86]. The investigators sought to determine whether the addition of SVR to CABG would reduce the rate of death or cardiac hospitalization in patients with anterior LV dysfunction. Since SVR was known to reduce LV volume, improve heart function, and increase LV ejection fraction (LVEF), STICH authors predicted adding SVR to CABG will have a positive effect on outcomes.

One thousand patients with ischemic HF, EF $\leq$35%, and a large anterior wall scar were enrolled in Hypothesis Two. Due to challenges with recruiting patients, inclusion criteria were modified and those with LV end systolic volume index $<$60 mL/m^2 were enrolled in the study. Cardiac magnetic resonance imaging, echocardiography, or computed tomography (CT) scan was used to determine function, volume, and wall motion at baseline and follow-up. The trial was designed based on intention to treat. Authors of Hypothesis Two found the addition of SVR to CABG had no effect on all-cause mortality or cardiac hospitalization.

Many groups have criticized the STICH trial for a variety of reasons, including myocardial viability testing, inclusion criteria, and the type of SVR that was performed. Over the years, Gerald Buckberg, who was a leading member of the RESTORE group, carried out important work pertaining to ventricular remodelling in ischemic cardiomyopathy [49, 87–95]. Along with Conte [96], he also presented balanced commentaries on the STICH trial [97–100]. Importantly, Buckberg emphasized that the success of SVR depended on appropriate LV reconstruction [10]. With respect to viability testing, there was no randomization, blinding, or control group. Also, different imaging modalities were used, which resulted in a non-standardized approach. The patient groups were not balanced, and power of analysis was restricted. Importantly, viability testing was not required in the updated study, further worsening selection bias. With respect to inclusion and exclusion criteria, STICH authors faced enormous challenges in enrolling patients. Therefore, instead of enrolling patients who stood to benefit most from an SVR, investigators loosened inclusion criteria. Indeed, in an important study, Dor [101] showed that a group of patients who would have been excluded from the STICH trial, benefited from an SVR procedure. Furthermore, STICH investigators had to also expand the number of centres that enrolled patients, perhaps influencing results by having inexperienced surgeons perform SVR. Further complicating the interpretation and application of results, it should be emphasized that the mean reduction in end-systolic volume obtained in the STICH trial was 19% against a required endpoint of 30%. Finally, with respect to the type of SVR, not all patients in the STICH trial received a standardized operation.

Despite controversies, the STICH trial provides some key lessons. It emphasizes the importance of designing a study that has clear inclusion criteria, which are based on accurately evaluating the benefits of a given procedure. Regardless of recruitment challenges, if an operative approach is being assessed, it must be undertaken in a patient population that stands to benefit from it. The study also underscores the critical nature of applying the most appropriate investigative tools and modalities. In this case, all centres should have used cardiac magnetic resonance imaging to confirm myocardial viability as other imaging options fail to provide an accurate estimation. Finally, prior to designing clinical trials that involve a surgical procedure, it is paramount to define and implement an operative approach that is standardized. In doing so, to minimize the influence inexperienced surgeons may have, a reasonable level of expertise should be required.

9. Predictors for poor outcomes and surgical ventricular restoration failure

Different studies have investigated factors that can result in poor outcomes post-SVR. Menicanti has shown that severe diastolic dysfunction, when associated with MR and a high NYHA functional class, is a risk factor for in-hospital mortality [81], which was also shown by Witkowski [102]. Post-SVR LV shape and volume are important determinants of long-term outcomes [103–106]. End systolic volume index of 80 to 120 has been suggested to be the ideal range for a successful SVR [23, 104, 105, 107, 108]. Furukawa and colleagues found that the preoperative degree of diastolic dysfunction can affect SVR outcomes [109]. Similar findings were also noted by Marui [110]. Not surprisingly, postoperative diastolic dysfunction can contribute to late mortality and cardiac events [111]. Preoperative right ventricular dysfunction has been suggested as a poor prognostic factor for post-SVR outcomes [112]. In this study right ventricle fractional area change was significantly associated with major adverse cardiac events and survival. Another study demonstrated that adequate residual remote myocardium is required to facilitate optimal outcomes for SVR. This is to ensure the operative reconstructive changes can lead to improvements in cardiac function [113]. This study found preoperative wall motion score index to be a alternative indicator of residual remote myocardial function. The authors suggest such an index can be used to better select patients in order to improve SVR outcomes. Moreover, increasing grade of MR [114] and poor renal function have been shown to adversely affect SVR outcomes [115]. Importantly, gender does not seem to affect the long-term outcomes for SVR [116].

Shipulin *et al.* [117] investigated the causes of continued and repeated LV remodelling after the Dor Procedure. The study considered 36 patients with previous large, focal infarcts, who underwent a Dor Procedure combined with CABG at 1-year follow-up. The authors found that lymphocytic-macrophage inflammatory infiltration combined with severe fibrosis were associated with unfavorable follow-up results post-SVR. The study introduced morphometrical parameters and quantitative metrics that could be used to measure coronary vessel conditions and volume capacity. They also showed an inverse relationship between content of natriuretic factor in the cardiomyocytes of right atrium auricle and the outcomes of the Dor procedure. In another study, Castelvecchio and colleagues found that left atrial volume is a powerful indicator of poor SVR outcomes [118]. More such studies are required to better assess the rate and potential reasons for a failed SVR operation.

10. Perspective

As reviewed here, there is mounting evidence in literature suggesting surgical ventricular restoration can be a safe a viable option for a specific cohort of patients who have ischemia-induced HF. Although concomitant procedures can affect outcomes, if applied to the appropriate patient, SVR can indeed produce reasonable results. Ongoing work is further assessing the benefits of SVR on LV remodelling at the cellular and molecular level. These studies should provide a more precise understanding of the effects of SVR on the residual myocardium and LV remodelling. There is also a concerted effort to define non-invasive markers that can be used to prognosticate the expected outcomes of SVR more accurately. Studies exploring the benefits of SVR to date have been limited by three major factors: (i) lack of a standardized SVR technique, (ii) small sample size, and (iii) short follow-up period. Although the Dor Procedure has taken the lion's share of what has been reported, modifications and other SVR approaches have provided enough evidence to suggest that they can also be applied to the appropriate patient population. As is the case with any intervention, it is crucial to design large, multi centre studies that are randomized and are intended to compare operative strategies that are standardized and performed by expert surgeons at centres of excellence. At a time when heart failure continues to affect millions globally, prospective donor hearts remain limited, and mechanical circulatory support systems have failed to guarantee optimal outcomes on a consistent basis, it is imperative to explore all available management options, including surgical ventricular restoration.

Author contributions

AFH was responsible for preparing original drafts and conducting revisions; for submitting the manuscript; and for conception of manuscript framework. ISA was responsible for providing supervision; and for final approval of the submission.

Ethics approval and consent to participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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