

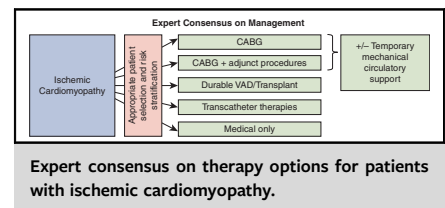
2021: The American Association for Thoracic Surgery Expert Consensus Document: Coronary artery bypass grafting in patients with ischemic cardiomyopathy and heart failure



ADULT

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It is estimated that more than 125 million people live with ischemic heart disease globally, and each year in the United States, 720,000 have a first myocardial infarction resulting in hospital admission or death.^{1,2} Approximately 35% of those who experience a coronary event in a given year die because of it, and each death is associated with an average of 16 years of life lost. Ischemic cardiomyopathy (ICM) is the single largest cause of heart failure (HF), although the underlying causes are often multifactorial and overlapping. More than 6 million people in the United States currently experience HF, and its prevalence is on the rise.^{1,3} In



CENTRAL MESSAGE

This expert consensus is on managing patients with ischemic cardiomyopathy, including triggers for specialized heart failure care, choice of surgical interventions, and measures to improve outcomes.

PERSPECTIVE

Sparse data are available to inform management of ischemic cardiomyopathy and heart failure. In addition to surgical revascularization, select patients may benefit from concomitant procedures such as mitral valve surgery. Temporary mechanical circulatory support may help in perioperative stabilization. In other scenarios, advanced heart failure therapies or nonsurgical management may be appropriate.

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Read at the 101st Annual Meeting of The American Association for Thoracic Surgery: A Virtual Learning Experience, April 30-May 2, 2021.

* AATS Cardiac Clinical Practice Standards Committee members and Invited Experts are listed in the Acknowledgments.

Received for publication April 17, 2021; accepted for publication April 20, 2021; available ahead of print April 30, 2021.

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J Thorac Cardiovasc Surg 2021;162:829-50
0022-5223/\$36.00

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<https://doi.org/10.1016/j.jtcvs.2021.04.052>

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Abbreviations and Acronyms

AATS	= American Association for Thoracic Surgery
AF	= atrial fibrillation
CABG	= coronary artery bypass grafting
CAD	= coronary artery disease
CRT	= cardiac resynchronization therapy
GDMT	= guideline-directed medical therapy
HF	= heart failure
HFrEF	= heart failure with reduced ejection fraction
IABP	= intra-aortic balloon pump
ICD	= implantable cardioverter-defibrillator
ICM	= ischemic cardiomyopathy
LAA	= left atrial appendage
LGE-CMR	= late gadolinium enhancement cardiac magnetic resonance
LV	= left ventricle/ventricular
LVEF	= left ventricular ejection fraction
LVESVI	= left ventricular end-systolic volume index
MAG	= multiarterial grafting
MCS	= mechanical circulatory support
MR	= mitral regurgitation
NYHA	= New York Heart Association
PCI	= percutaneous coronary intervention
PCS	= postcardiotomy shock
RCT	= randomized controlled trial
RV	= right ventricle/ventricular
STICH	= Surgical Treatment for Ischemic Heart Failure
STS	= Society of Thoracic Surgeons
SVR	= surgical ventricular restoration
TR	= tricuspid regurgitation
VAD	= ventricular assist device
VA-ECMO	= veno-arterial extracorporeal membrane oxygenation
VT	= ventricular tachycardia

addition to the human toll, the estimated cost of HF exceeds \$40 billion each year.^{4,5}

Surgical revascularization, performed on an estimated 350,000 patients annually in the United States,² has multiple potential benefits, including reestablishing adequate blood flow to undersupplied myocardial territories, reversing myocardial hibernation, and preventing future ischemia and infarction. However, patients with coronary artery disease (CAD) complicated by ICM, particularly in the presence of HF and other end-organ dysfunction, represent a higher-risk population with specific considerations and challenges. For example, in addition to coronary artery

bypass grafting (CABG), selected patients may benefit from concomitant procedures such as mitral valve surgery or a ventricular remodeling procedure. Temporary mechanical circulatory support (MCS) may be helpful to stabilize selected patients in the perioperative period and improve patient outcomes. In other scenarios, advanced HF therapies, including durable ventricular assist device (VAD) implantation or cardiac transplantation, may be appropriate. Nonsurgical interventions such as percutaneous coronary intervention (PCI) and transcatheter mitral valve therapies may also be considered. Decision making can be particularly difficult because sparse data are available to inform clinical management pathways, particularly when surgical therapies are contemplated.

The goal of this expert consensus document is to provide a practical framework for managing patients with ICM, including triggers for specialized HF care, preoperative optimization, surgical interventions, and other measures that can improve patient outcomes. It provides general guidance based on available evidence and prevailing opinions regarding best practices in this domain.

DEFINITIONS AND SCOPE

- The focus of this document is CABG in patients with ICM and HF.
- ICM is defined as left ventricular (LV) dysfunction caused by CAD, with or without clinical HF.
- Unless otherwise specified, ICM refers to patients with a LV ejection fraction (LVEF) $\leq 35\%$.
- Although some recommendations may be relevant to patients with CAD and LVEF $>35\%$, this document primarily focuses on managing patients with CAD and LVEF $\leq 35\%$.
- This document does not address emergency surgical interventions in patients with cardiogenic shock complicating acute myocardial infarction. In addition, detailed assessment and treatment of patients who may benefit from advanced HF surgical therapies (such as durable VAD and cardiac transplantation) is beyond its scope.
- The Expert Consensus Writing Group endorses the evidence-based approaches to CAD and HF management provided in the 2013 American College of Cardiology Foundation/American Heart Association (ACCF/AHA) guidelines for the management of HF,⁵ the 2015 American Association for Thoracic Surgery consensus guidelines for ischemic mitral valve regurgitation,⁶ the 2011 ACCF/AHA guidelines for CABG,⁷ the 2016 Society of Thoracic Surgeons (STS) clinical practice guidelines on arterial conduits for CABG,⁸ the 2018 European Society for Cardiology/European Association for Cardio-Thoracic Surgery (ESC/EACTS) guidelines on myocardial revascularization,⁹ the 2008 ACC/AHA/Heart Rhythm Society guidelines on device-based

therapy for cardiac rhythm abnormalities,¹⁰ and, when applicable, their subsequent updates.¹¹⁻¹⁴

- Patient preferences and values, in conjunction with evidence-based clinical judgment, should complement the present document in clinical decision making.
- The recommendations in this document are subject to change in light of new data.

METHODS

In developing this document, we followed the recommendations of the AATS/STS position statement on developing clinical practice documents.¹⁵ Much of the published literature regarding managing patients with ICM and HF is based on single-center, noncomparative case series. Because higher-level evidence in this domain is sparse, an expert consensus document pathway was adopted, wherein an expert panel of 16 cardiac surgeons and 2 cardiologists used their best judgment to make consensus statements designed to inform patient care.

Literature searches were conducted using 3 databases (Medline, Embase, and Cochrane) with prespecified search terms and search strategy (Table E1). All studies published from January 1, 2010, through September 3, 2020, were reviewed by the writing group chairs and shared with group members to identify relevant studies to be used in evidence synthesis. Older key publications and additional publications not otherwise identified by the aforementioned literature search were included based on recommendations from group members and invited experts.

A modified Delphi process¹⁵ with an online voting platform was used, with 80% participation and at least 75% agreement between writing group members required to achieve consensus. Each writing group member and invited external expert was asked to consider each recommendation with regard to class and level of evidence.

Controversies were discussed and resolved via conference calls and virtual discussions. A final draft was prepared by the writing group chairpersons. Writing group members and invited experts were given ample opportunity to review, comment, and approve the draft before it was submitted to The AATS Cardiac Clinical Practice Standards Committee and the Board of Directors for approval.

PATIENT WORKUP (Table 1)

Patients with ICM can present with a spectrum of disease severity ranging from no or minimal symptoms to advanced HF. Preoperative workup starts by determining whether the degree of cardiomyopathy and associated symptoms is

adequately explained by severity of the CAD. If not, other (nonischemic) contributing causes of cardiomyopathy should be ruled out. Patients with HF and those with high-risk features listed in Figure 1 should be referred and managed at a center with a comprehensive HF program (see the Program Characteristics and Quality Indicators Section).

Diagnostic Testing

In addition to standard coronary angiography to define the extent and severity of coronary disease and echocardiographic assessment of ventricular and valve function, assessment of myocardial ischemia and viability may be helpful in patients with ICM, especially those with HF and other high-risk features (see Figure 1).

Stress echocardiography and nuclear stress-test imaging are among the commonly used modalities for assessing ischemia. Late gadolinium enhancement cardiac magnetic resonance (LGE-CMR), dobutamine echocardiography, single-photon emission computed tomography, and F-18-fluorodeoxyglucose positron emission tomography imaging can be used to assess myocardial viability.¹⁶ Most of the members of this expert panel favor LGE-CMR for viability assessment, but this is based on limited data and indirect comparisons of the aforementioned imaging modalities. Imaging-based but not clinically validated algorithms have been proposed to recommend medical management over revascularization if the transmural extent of the LGE-CMR-measured scar is >50% of wall thickness, a cutoff that has a 90% negative predictive value for segmental recovery after revascularization.¹⁶ However, a recent study demonstrated that more than one-third of myocardial segments with a transmural extent of LGE >50% showed improved wall motion after CABG.¹⁷ Degree of the ischemic burden and contractile reserve can be incorporated as additional considerations in the decision algorithm.¹⁶ However, data about the usefulness of ischemia and viability testing are nuanced.

TABLE 1. Multidisciplinary heart failure team consultation and patient workup

COR	LOE	Recommendations
I	C-EO	Evaluation by a multidisciplinary heart failure team should be part of the preoperative workup for patients with ischemic cardiomyopathy and high-risk features (see Figure 1)
I	C-EO	Referral to a heart failure center is recommended if the patient may benefit from advanced heart failure therapies
IIa	B-NR	Viability assessment can be helpful to determine prognosis and management

COR, Class of recommendation; LOE, level of evidence; EO, expert opinion; NR, nonrandomized.

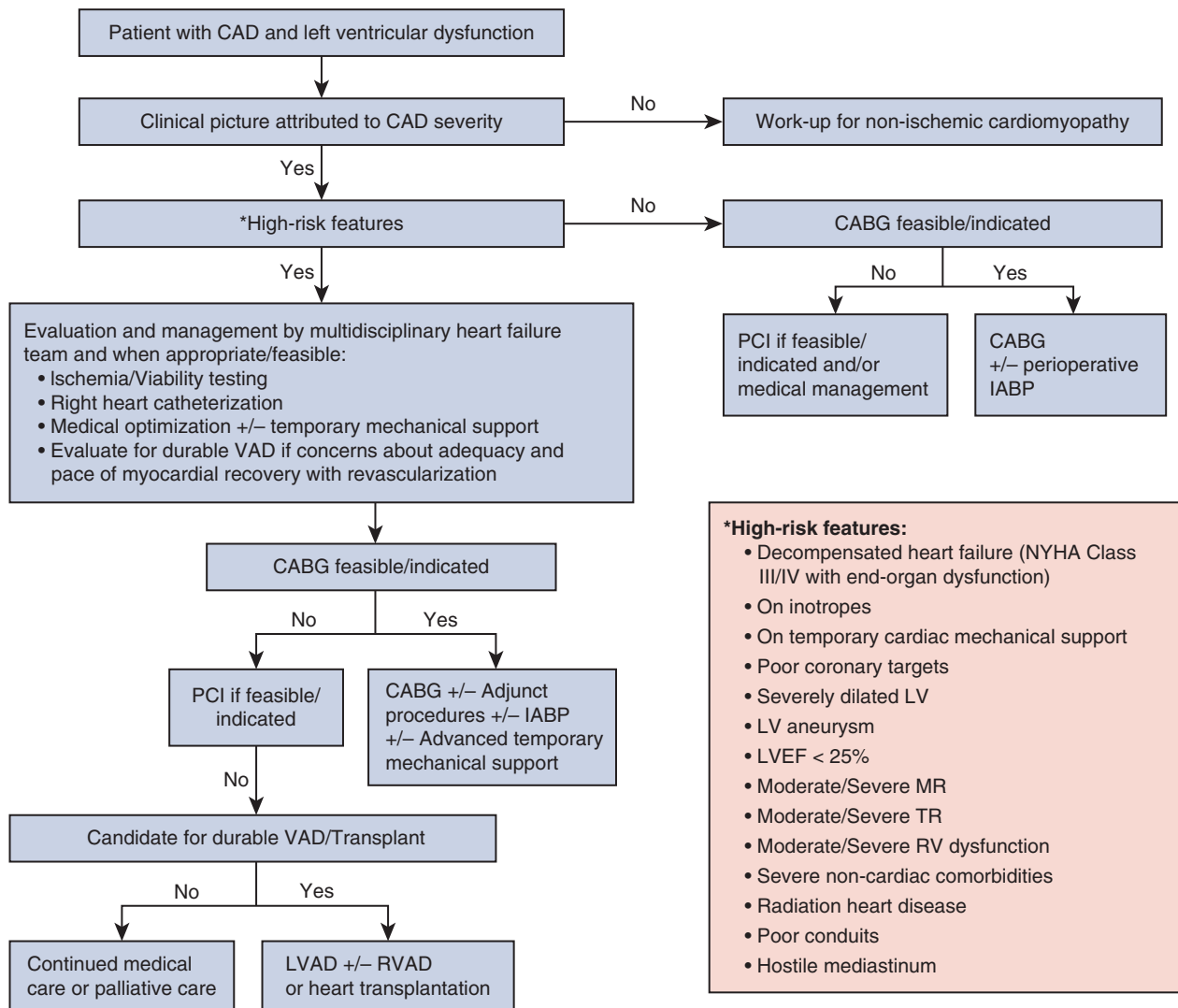


FIGURE 1. Overview of the management of patients with coronary artery disease and left ventricular dysfunction. CAD, Coronary artery disease; NYHA, New York Heart Association; LV, left ventricular; LVEF, left ventricular ejection fraction; MR, mitral regurgitation; TR, tricuspid regurgitation; RV, right ventricular; PCI, percutaneous coronary intervention; CABG, coronary artery bypass grafting; IABP, intra-aortic balloon pump; VAD, ventricular assist device; LVAD, left ventricular assist device; RVAD, right ventricular assist device.

A subgroup analysis of the Surgical Treatment for Ischemic Heart Failure (STICH) trial showed that inducible myocardial ischemia does not identify patients with greater benefit from CABG over optimal medical therapy.¹⁸ Patients with viability had lower long-term mortality than those who did not show any signs of viability, and there was significant improvement in LVEF in patients who demonstrated myocardial viability, regardless of treatment strategy. However, the outcome after CABG was not significantly different in patients who had viability compared with those who did not.¹⁹ Improvement in LVEF was also similar in patients with viability who underwent revascularization versus those treated with medical therapy.¹⁹ Only half of the patients underwent viability testing, and its assessment was not standardized, precluding definitive

conclusions. Yet similar findings were reported in the F-18-Fluorodeoxyglucose Positron Emission Tomography Imaging-assisted Management of Patients with Severe Left Ventricular Dysfunction and Suspected Coronary Disease trial, where the composite primary outcome of cardiac death, myocardial infarction, or recurrent hospital stay for cardiac cause within 1 year was not different in patients randomized to viability assessment versus no viability assessment.²⁰ However, the primary outcome was improved in the subgroup of patients for whom viability-guided management was actually implemented.

A meta-analysis of nonrandomized and randomized studies reported that the usefulness of myocardial viability tests for decision making concerning revascularization in ICM was inconclusive.²¹ Nevertheless, viability testing

could still play a useful role in clinical practice, especially in high-risk patients with advanced age or significant comorbidities when the risks and benefits of revascularization remain unclear and absence of viability may tilt the balance against CABG. Assessment of viability and detection of ischemia is recommended by the guidelines for treatment of CAD because of its presumed effect on prognosis.⁹

The Heart Team and the Patient

Once all diagnostic information is available, the patient should be discussed by a multidisciplinary heart team. Input of team members with specific HF expertise is important for patients with HF or at high risk for CABG (see Figure 1). An abbreviated advanced HF workup that includes evaluation for anatomical, medical, and social risk can help determine whether a patient is a suitable candidate for advanced therapies (durable MCS or heart transplantation) if the need arises.

As part of the discussion with patients and their family about treatment options and the associated risks and benefits, it is important to bring up the possible need for temporary or durable MCS at the time of the initial consent for CABG. This is particularly relevant given the current trend of increased use of temporary MCS in treating postcardiomy cardiogenic shock.²²

By involving patients and families in shared decision making, the care team avoids the pitfalls of paternalism and maximizes the principle of autonomy. This allows decisions surrounding care to occur in a nonemergency setting with time to process information, enabling patients and families to make better decisions and build trust with the surgical team.²³

TREATMENT

Management of patients with ICM can range from medical therapies to an array of transcatheter interventions and surgical therapies tailored to the anatomy of the coronary disease, symptom severity, associated cardiac pathologies, and noncardiac comorbidities. The primary focus of this section is surgical coronary revascularization and the indications for various surgical procedures that can supplement CABG. Scenarios in which advanced HF therapies may be considered as first-line treatment are also reviewed.

Revascularization Modalities

Only 3 randomized clinical trials have been published on the use of CABG versus PCI or medical therapy alone in patients with ICM.²⁴⁻²⁷ The largest, the STICH trial from which most recommendations in this current area are derived, did not include a PCI arm.²⁵ The follow-up extension of the STICH trial revealed that CABG confers a survival benefit over medical therapy alone in patients with ischemic HF, with 16% higher survival and 21% better

freedom from death due to cardiovascular causes at 9.8 years.²⁸ Nonetheless, findings of the STICH trial have been scrutinized for several reasons, including what appears to be an excessively high 30-day mortality of 3.6% in the CABG arm, crossover of 17% from medical therapy to CABG and 9% from CABG to medical therapy over the follow-up period (median, 56 months), low use of implantable cardioverter-defibrillators (ICDs), now-antiquated medical therapy for HF, and likely preferential enrollment of patients considered to need surgical ventricular reconstruction (a prime hypothesis at the time that may have resulted in less complete revascularization and higher perioperative mortality).

In the observational realm, several large studies have compared CABG with PCI for CAD patients with LV systolic dysfunction. These were summarized by Wolff and colleagues²⁴ in a 2017 meta-analysis that reported an 18% survival benefit for CABG at a median follow-up of 3 years. A study by Bangalore and colleagues²⁹ used data from the New York State Reporting System registries and indicated that use of PCI with everolimus-eluting stents versus CABG correlated with equivalent survival over a follow-up of 2.9 years. Notably, patients who received PCI had more than twice the prevalence of myocardial infarction and repeat revascularization, while patients undergoing CABG experienced approximately twice as many strokes.

The largest observational study on the topic of CAD with LV systolic dysfunction was reported by Sun and colleagues³⁰ in 2020. In their population-based study from Ontario, Canada, 4794 patients with LVEF <35% and left anterior descending, left main, or multivessel CAD who underwent PCI or CABG were propensity matched. At a mean of 5.2 years, patients who received PCI had significantly higher mortality (hazard ratio [HR], 1.6), death from cardiovascular disease (HR, 1.4), major adverse cardiac events (HR, 2.0), subsequent revascularization (HR, 3.7), and hospitalization for myocardial infarction (HR, 3.2) and HF (HR, 1.5) than matched patients who underwent CABG, although some variables such as dementia and the Charlson comorbidity index remained unbalanced after propensity matching.

The influence of complete versus incomplete revascularization, which was a correlate of PCI efficacy in the study by Bangalore and colleagues,²⁹ remains to be elucidated for CABG, although some studies suggest a benefit in patients receiving complete revascularization, including the elderly.³¹ Diabetes appears to be an amplifier of the beneficial effects observed in patients with ICM undergoing CABG versus PCI; this was observed both in a dedicated cohort³² and by a positive statistical interaction in the recent study by Sun and colleagues.³⁰

In summary, the totality of available evidence associates CABG with superior outcomes compared with alternative therapies and makes it the recommended treatment for

patients with ICM in whom the surgical risk–benefit ratio is favorable. However, a modern trial comparing CABG, PCI, and medical therapy alone appears warranted because it would address several criticisms of the STICH trial, including improved early CABG mortality with the advent of modern CABG techniques and improved perioperative care, as well as the more selective and appropriate use of surgical ventricular reconstruction (SVR). Moreover, the role of PCI is now better understood, including use of fractional flow reserve to guide intervention. In addition, major improvements in medical therapies for HF have occurred over the past decade and would be appropriately implemented in a modern trial.

Preoperative Optimization and Perioperative Temporary Mechanical Support (Tables 2 and 3)

Patient factors that have been consistently associated with adverse outcomes after CABG include preoperative renal dysfunction,^{33–35} advanced degrees of HF,^{34,35} and hemodynamic instability.^{33,35} Acknowledging the clinical characteristics that portend poor outcomes allows for preoperative optimization that can improve patient status at the time of operation.

The specific mode of optimization can be individualized to patients' needs and driven by their response to initial therapy. If medical therapy alone is ineffective, more intensive/invasive measures can be considered. In a variety of analyses, prophylactic intra-aortic balloon pump (IABP) therapy before operation has been noted to result not only in improved patient condition before CABG,^{36,37} but also in reduced perioperative morbidity and mortality.^{38,39} Much of the improvement in clinical status associated with prophylactic IABP therapy may be explained by improvement in preoperative cardiac index, elegantly demonstrated in a prospective, randomized study.³⁷ Two

meta-analyses of randomized clinical trials examining the utility of preoperative IABP therapy demonstrated a strong association with lower hospital mortality, reduced low cardiac output syndrome, and shorter intensive care unit stay.^{38,39} Low ejection fraction, left main disease >70%, reoperative status, poor coronary targets, and unstable angina constituted the typical patient risk profile for which preoperative IABP has demonstrated benefit.³⁹

In the setting of patients who present with cardiogenic shock resulting from myocardial infarction or severe decompensated HF with end-organ dysfunction, an IABP may be inadequate for stabilization or preoperative optimization before high-risk CABG. Indeed, because of the limited ventricular unloading afforded by the IABP, interest is rising in use of transvalvular devices that can fully pressure and volume unload the dysfunctional LV.⁴⁰ For patients with an anticipated need for postoperative MCS, such devices have also been used safely and successfully in the preoperative setting for optimization and continued after operation for early postoperative hemodynamic support before successful weaning.^{40–42} For patients who reverse their organ dysfunction and acidosis with temporary MCS and demonstrate adequate contractile reserve and response to inotropic stimulation, a successful bridge to CABG is in sight. This is contingent on good coronary targets and absence of unfavorable anatomic and physiologic profiles that favor a durable MCS option (see [Advanced HF Therapies as First-line Therapy](#) Section).

For patients with isolated LV systolic dysfunction undergoing CABG without worrisome clinical factors such as decompensated HF, advanced adverse LV remodeling, evidence of end-organ dysfunction, or anticipated need for postoperative MCS, specific interventions for preoperative optimization may not be required. However, because outcomes are strongly associated with these detracting clinical

TABLE 2. Preoperative patient optimization

COR	LOE	Recommendations
I	B-R	An intra-aortic balloon pump should be considered in patients with active/decompensated heart failure, advanced adverse left ventricular remodeling, evidence of end-organ dysfunction, or anticipated need for postoperative mechanical support
Iib	C-LD	Advanced mechanical support options may be considered in patients with active/decompensated heart failure, advanced adverse left ventricular remodeling, evidence of end-organ dysfunction, or anticipated need for postoperative mechanical support, especially if intra-aortic balloon pumping does not provide sufficient support

COR, Class of recommendation; LOE, level of evidence; R, randomized; LD, limited data.

TABLE 3. Preoperative optimization strategies

Strategy	Indications/timing
Medical	Volume status optimization, inotropes as needed
Invasive hemodynamic monitoring	When volume status is unclear or labile hemodynamic status
Intra-aortic balloon pump	Decompensated heart failure, poor tissue perfusion, progressive organ dysfunction, rising lactate, or cardiac index <2.0 L/min/m ² on inotropic support Down-titrate inotropic drug doses Stabilize operative course, anticipated intraoperative difficulties, or concerns about delayed myocardial recovery First-line mechanical support
Temporary VAD or ECMO	Second-line mechanical support option if intra-aortic balloon pump does not provide sufficient support Ideally inserted at a heart failure center

VAD, Ventricular assist device; ECMO, extracorporeal membrane oxygenation.

factors, if present, the aforementioned approaches to preoperative optimization should be considered before high-risk CABG.

CABG Strategy (Tables 4 and 5)

On-pump arrested-heart CABG. The goal of CABG is to achieve expeditious and complete revascularization. On-pump arrested heart is the most common CABG strategy,⁴³ affording a bloodless and still field that facilitates complete revascularization.⁴⁴ Excellent myocardial protection is paramount in the setting of ICM. Myocardial ischemia and injury are poorly tolerated when myocardial reserve is limited. Controversy exists regarding which cardioplegic solution, temperature, and route of administration provides optimal myocardial protection.

The bulk of studies on myocardial protection enrolled mainly patients with preserved LV function, and patients undergoing valve surgery were often included. Most studies compared blood versus crystalloid solutions, and these consistently support the superiority of blood cardioplegia. A meta-analysis of 12 studies, including 2866 patients, found that prevalence of perioperative myocardial infarction was lower in patients who received blood cardioplegia.⁴⁵ Conversely, no definitive data exist on the superiority of warm over cold cardioplegia. A meta-analysis of 41 randomized clinical trials (RCT) found that warm cardioplegia did not improve clinical outcomes, but was associated with a mild reduction of cardiac enzyme release.⁴⁶

Despite mainly observational studies suggesting an advantage of single over multidose cardioplegia, the benefit was generally limited to a reduction in ischemia and bypass times and did not translate into a major morbidity or mortality advantage.⁴⁷ In addition, caution should be used when extrapolating these data to patients with ICM and right ventricular (RV) dysfunction.^{48,49}

No systematic comparison of different cardioplegia administration routes (ie, antegrade vs retrograde) exists. However, animal studies have shown that compared with

antegrade delivery, retrograde cardioplegia provides heterogeneous perfusion, and its ability to protect the RV myocardium is unpredictable.⁵⁰ Therefore, use of retrograde cardioplegia in isolation should be avoided. On the other hand, retrograde cardioplegia delivery may be useful in redo CABG to reach territories not otherwise reachable by antegrade delivery, and to flush potential embolic debris from inadvertently manipulated diseased vein grafts.^{48,51} Similarly, distribution of cardioplegia may be compromised in territories with severe CAD, and retrograde cardioplegia may supplement protection in those territories. A myocardial temperature probe can be helpful in verifying adequate myocardial cooling as a surrogate for cardioplegia delivery.

Although data are scarce, it has been reported that antegrade cardioplegia supplemented with venous graft perfusion can significantly improve myocardial protection. In a small RCT, consecutive patients scheduled for isolated CABG were randomized to receive either continuous crystalloid cardioplegia via vein grafts on completion of each distal anastomosis plus intermittent blood cardioplegia through the aortic root (treatment group, n = 110), or antegrade blood cardioplegia alone (control group, n = 113). Inotrope and IABP demand during weaning were significantly higher in the control group (31.8% vs 20% [$P = .043$] and 7.9% vs 1.8% [$P = .034$], respectively).⁵² The most suitable myocardial protection strategy may be a combination of antegrade, retrograde, and delivery down vein grafts.

Alternatives to on-pump, arrested-heart CABG.

Off-pump CABG. From the outset, it must be recognized that there have been no RCTs of on-pump versus off-pump surgery in this specific cohort of patients, and that in the RCTs that do compare on- and off-pump surgery, very few patients with significant LV dysfunction were included. In addition to all the usual caveats regarding nonrandomized data, a further limitation is that the vast majority of these individual observational studies report only in-hospital or short-term (30-day) outcomes. This is of particular relevance given that some reports note that

TABLE 4. Coronary artery bypass graft strategies and myocardial protection

COR	LOE	Recommendations
I	B-NR	When using standard on-pump techniques, minimizing myocardial ischemic time and meticulous myocardial preservation techniques are recommended
I	B-NR	Blood cardioplegic solution is preferred over crystalloid cardioplegic solution
IIa	B-NR	In patients with a favorable risk profile, the left internal thoracic artery should be considered to bypass the left anterior descending artery because of the associated survival advantage
IIb	B-NR	Multiarterial grafting may be considered in select patients with confirmation of viable myocardium provided the surgeon has appropriate expertise and experience in performing multiarterial grafting in this setting
IIb	B-NR	Off-pump or on-pump beating-heart coronary artery bypass grafting may be considered provided the surgeon has appropriate expertise and experience in the chosen approach in this setting

COR, Class of recommendation; LOE, level of evidence; NR, nonrandomized.

off-pump surgery may lead to impaired long-term outcomes, especially if performed by inexperienced operators and/or accompanied by incomplete revascularization.⁵³

In a 2011 meta-analysis of 23 individual nonrandomized studies⁵⁴ involving 7759 CABG patients with LVEF <40%, 2822 underwent off-pump surgery. Overall early mortality was significantly reduced (odds ratio [OR], 0.64; 95% CI, 0.51-0.81) in this group and, in particular, also in the subpopulation of 1915 patients with LVEF <30% (OR, 0.61; 95% CI, 0.47-0.80). A more recent (2020) meta-analysis⁵⁵ comprising 16 studies with 32,354 patients with LV dysfunction (defined as LVEF <40%) also reported a significant reduction in 30-day mortality (OR, 0.84; 95% CI, 0.73-0.97) and in perioperative complications and transfusion requirements. In a 2016 report from the Japan Adult Cardiovascular Surgery Database,⁵⁶ 918 pairs of propensity-matched CABG patients with LVEF <30% were reported to have lower intraoperative and 30-day mortality with off-pump CABG (1.7% vs 3.7%; $P = .01$) and also lower prevalence of mediastinitis, reoperation for bleeding, and prolonged ventilation, but no difference in stroke or renal failure.

On-pump beating-heart CABG. On-pump beating-heart CABG has also been proposed as an alternative strategy to on-pump cardioplegic arrest, particularly in higher risk patients, including those with impaired LV function.⁵⁷ In a review of 11 such studies, comprising 2 RCTs and 9 observational studies, mortality was similar with both

techniques in the RCTs, whereas lower mortality was reported with the on-pump beating-heart technique in 5 of the observational studies. Because of lack of randomization and absence of propensity matching, the possibility of selection bias accounting for the difference in mortality cannot be discounted. However, in 1 RCT, the beating-heart group had a significant increase in biochemical and cardiac magnetic resonance imaging-determined myocardial infarction,⁵⁸ with the latter persisting at 6 months. The most likely mechanism of increased intraoperative myocardial injury with the on-pump beating-heart technique was inadequate coronary perfusion distal to severe proximal coronary stenosis,⁵⁸ implying the importance of maintaining a higher perfusion pressure with this method.

Bypass conduits. There is general agreement among experts that multiarterial grafting (MAG) is associated with superior outcomes in appropriately selected patients undergoing CABG.^{8,9} However, the evidence is generally derived from study populations comprising few patients with severe ventricular dysfunction.⁵⁹⁻⁶¹

The overriding priority in patients with ICM is to mitigate the upfront risk of surgery. The HR for perioperative mortality after isolated CABG is 1.19 (95% CI, 1.17-1.22) for every 10% reduction in LVEF.⁶² Operative risk is compounded when adding noncardiac organ dysfunction and other comorbidities that patients with severe ventricular dysfunction are prone to have.

TABLE 5. Coronary artery bypass grafting strategies: Features and applications

Strategy	Pros	Cons	Appropriate application
On-pump, cardioplegic arrest	<ul style="list-style-type: none"> • Bloodless and still operative field • Facilitates complete revascularization • Hemodynamic stability 	<ul style="list-style-type: none"> • Physiologic insult of cardiopulmonary bypass and associated morbidity (eg, increased risk of bleeding and blood transfusion, atrial fibrillation) • Global myocardial ischemia (blunted with meticulous myocardial protection) 	<ul style="list-style-type: none"> • Default technique
Off-pump	<ul style="list-style-type: none"> • Reduced perioperative morbidity 	<ul style="list-style-type: none"> • Increased risk of incomplete revascularization • Potential risk of reduced long-term survival • High morbidity and mortality associated with conversions from off- to on-pump, particularly unplanned conversions • Potential reduced graft patency 	<ul style="list-style-type: none"> • Surgical expertise • Hemodynamic stability • Diseased ascending aorta
On-pump beating heart	<ul style="list-style-type: none"> • Avoid ischemic arrest • Preserve right ventricular perfusion 	<ul style="list-style-type: none"> • Risk of watershed myocardial infarction, especially with reduced perfusion pressures 	<ul style="list-style-type: none"> • Surgical expertise • Diseased ascending aorta (clamping contraindicated or associated with increased risk) • May be helpful in patients with significant right ventricular dysfunction
Multiarterial grafting	<ul style="list-style-type: none"> • Potential for improved long-term graft patency and improved longevity 	<ul style="list-style-type: none"> • Risk of insufficient early conduit blood flow • Risk of conduit spasm, particularly in patients on high doses of vasopressor support • May prolong operative and myocardial ischemic time • Insufficient conduit length in a dilated heart 	<ul style="list-style-type: none"> • Surgical expertise • Young patients with absence of severe noncardiac comorbidities that can limit their survival • Poor vein conduits • Expected low postoperative vasopressor dose

Perioperative myocardial ischemia should be avoided, which should drive the choice of conduits used in bypassing weak ventricles. There are 4 reasons why caution should be used when contemplating MAG in this population: First, perioperative administration of high doses of vasopressors may be necessary, and this is a predisposing factor for development of spasm in arterial grafts.⁶³ Radial and gastroepiploic arteries are particularly vulnerable to spasm compared with internal thoracic arteries. Second, adequacy of flow in a fresh arterial graft may not be as robust as that in a vein graft,⁶⁴ with the potential for clinically significant early coronary hypoperfusion.^{65,66} Third, MAG usually adds to the complexity and length of the operation and prolongs myocardial ischemic time, which may not be well tolerated in patients with severe ventricular dysfunction. Fourth, arterial grafts may not be of adequate length in massively dilated hearts, especially if sequential anastomoses are contemplated.

A patient-level combined analysis of 6 RCTs associated radial artery grafts with improved clinical outcomes compared with venous grafts.⁶⁷ In the subgroup analysis, LVEF <35% did not modify the treatment effect, but the number of patients with LVEF below 35% was only 25 (4.7%) and 32 (6.4%) in the radial and saphenous vein groups, respectively. Observational studies yielded mixed results for use of MAG in patients with reduced LVEF, with some showing benefit⁶⁸⁻⁷⁰ and others no benefit.^{60,71,72} The cutoff for LVEF varied (lowest limit <30%), which adds to the uncertainty regarding MAG benefits, particularly in patients with very low LVEF.

Although MAG is not routinely recommended for patients with severe ventricular dysfunction, in some scenarios its use may be considered. Surgeon experience and judgment, coupled with appropriate patient selection, are paramount to ensure good outcomes.⁷³ Observational evidence suggests that the benefit of MAG is lost in patients

with limited life expectancy or severe comorbidities.^{71,74-76} Therefore, young patients with compensated HF deemed to be suitable candidates for CABG may be considered for MAG if the risk–benefit ratio is favorable and prolonged survival is anticipated after revascularization.

CABG Combined With Other Procedures

Mitral valve surgery (Tables 6 and 7). In the Cardiothoracic Surgical Trials Network, adding surgical mitral valve repair to CABG in patients with moderate ischemic mitral regurgitation (MR) had no significant effect on survival, overall reduction of adverse events, or LV reverse remodeling at 2 years, but was associated with increased duration of postoperative stay and morbidity, including neurological events and atrial arrhythmias.⁷⁷ However, the trial did not specifically focus on patients with low LVEF. Of note, an effective regurgitant orifice area ≤ 0.2 cm² plus additional criteria to define moderate MR were used, and no clear conclusions can be drawn concerning patients with an effective regurgitant orifice area >0.2 cm², which in observational studies has been linked to higher risk of cardiovascular events. Smaller RCTs showed a benefit in surrogate outcomes for CABG and mitral valve repair versus CABG alone in patients with moderate ischemic MR.^{78,79} Observational evidence on the topic is mixed.⁸⁰⁻⁸³

In patients with severe functional ischemic MR, mitral valve replacement has been shown to provide more reliable and durable relief of MR than repair, but with no survival benefit over repair.⁸⁴ Mitral valve replacement rather than repair is favored in patients with LV basal aneurysm/dyskinesia or other potential risk features for recurrent MR after repair (Table 7).¹³ Preserving the subvalvular apparatus is strongly recommended when replacing the mitral valve in this patient cohort.

Concerns about persistent tethering of the posterior leaflet, leading to recurrent MR, have prompted some to combine mitral anuloplasty with a subvalvular procedure, such as papillary muscle approximation and papillary muscle relocation. The reported echocardiographic and cardiovascular outcomes are encouraging, but show no influence on all-cause mortality or quality of life.^{85,86} Therefore, this remains an area for further study and evaluation.

Tricuspid valve surgery. Tricuspid regurgitation (TR) is an established risk marker in patients undergoing CABG.⁸⁷ In patients undergoing surgery for ischemic MR, progression of unrepaired non-severe TR is uncommon. However, TR progression and presence of moderate or greater TR are associated with clinical events.⁸⁸

Current AHA/ACC guidelines assign a class I recommendation for tricuspid valve repair at the time of left-sided valve surgery for severe TR and class IIa for less severe TR in the presence of anular dilatation (>4.0 cm) or right-sided HF.⁸⁹

The underlying etiology of TR in patients with ICM and HF is varied and includes tricuspid anular dilatation and leaflet tethering in the setting of RV remodeling with or without pulmonary hypertension, anular dilatation associated with atrial fibrillation (AF), or iatrogenic, related to RV device leads.⁸⁹ Severe TR in the presence of significant RV dysfunction is a particularly high-risk feature that warrants assessment and consideration for advanced HF therapies.

SVR (Table 8). The conceptual rationale for including SVR at the time of CABG in patients with advanced ICM resides in correcting adverse remodeling of the LV in hopes of improving ventricular function and clinical outcomes. With progressive LV dilatation, there is a transition from the normal elliptical ventricular geometry to a spherical shape that impairs the structure–function relationship.⁹⁰ Tenets of the operation that may confer the most benefit to patients include resection of scarred myocardium, reducing ventricular size, and restoring an anatomically elliptical shape.⁹¹ With these aims in mind, it remains uncertain which patients should receive this as part of the CABG operation and what the impact is on long-term survival and functional outcome.

Significant LV dilatation after myocardial infarction is known to portend poor prognosis,⁹² and case series and registry data demonstrate improvement in New York Heart Association (NYHA) functional class, ventricular size and function, hemodynamic parameters, and neurohormonal milieu after SVR.⁹³ Consequently, the STICH trial was conducted to evaluate outcomes of SVR at the time of CABG with criteria that included LV dysfunction, LV akinesis/dyskinesia, presence of scar, and LV dilatation.⁹⁴ The trial concluded that CABG with SVR did not improve functional outcomes or reduce death or hospitalization compared with CABG alone. The trial was controversial in that patients with true, thin-walled dyskinetic aneurysms were studied in the same group as those with akinetic thick-walled areas of mixed scar and viable muscle. In addition, accurate measurements of LV dimensions and the modest degree of LV end-systolic volume index (LVESVI) improvement with SVR were subjects of criticism.^{95,96}

Learning from the limitations of STICH and incorporating predictors of favorable outcomes derived from observational studies, the data suggest that in select patients with appropriate criteria of absent viability, dyskinesia $\geq 35\%$ of the anterior wall, and LVESVI ≥ 60 mL/m², an SVR achieving a $>30\%$ reduction in LVESVI is closely tied to postoperative LV size and improved clinical outcomes.⁹⁵⁻⁹⁷

Rhythm-related surgery (Table 8).

AF. Current clinical practice guidelines recommend concomitant surgical ablation and left atrial appendage (LAA) exclusion for AF at the time of CABG or when CABG is combined with valvular surgery.⁹⁸ Along with

TABLE 6. Concomitant mitral valve procedure

COR	LOE	Recommendations
I	B-NR	Concomitant mitral valve surgery is indicated in patients with severe mitral regurgitation
IIb	B-NR	Concomitant mitral valve surgery may be considered in patients with moderate mitral regurgitation (see Table 7).

COR, Class of recommendation; LOE, level of evidence; NR, nonrandomized.

the anticipated long-term benefit related to sinus rhythm restoration, including reduced risk of stroke, surgical ablation can improve LV function by restoring the “atrial kick.”⁹⁸ However, the rationale for concomitant surgical ablation for AF at the time of CABG in the setting of poor LV function is controversial. Surgical ablation can prolong ischemic time, which may not be well tolerated in this patient population and can potentially adversely affect short-term outcomes.

Data demonstrating a benefit from surgical ablation in patients with AF undergoing isolated CABG are scarce. Most RCTs include patients with valvular disease, and evidence of beneficial effects on hard clinical end points is lacking.⁹⁹

Evidence for the efficacy of surgical ablation in patients undergoing isolated CABG is derived mainly from observational studies,^{100,101} in which residual selection bias still exists (eg, ablation may be preferentially performed on healthier patients), and the proportion of patients with reduced LV function is very limited. In a large Medicare-linked STS database study,¹⁰⁰ among 34,600 CABG patients with preoperative AF, 10,541 (30.5%) were treated with surgical ablation and 23,059 were not. LV function was normal in almost half of the patients, and only 22% were in NYHA class IV. Concomitant ablation was associated with lower stroke or systemic embolization and mortality in patients who survived more than 2 years, but with no difference in the shorter term.

An important consideration in the early postoperative period relates to LAA management. The LAA plays a major

role in adaption to pressure and volume overload and is among the main sources of atrial natriuretic peptide and brain natriuretic peptide.¹⁰² Our knowledge regarding the hemodynamic and neurohormonal consequences of LAA elimination in the HF population is limited.

It is therefore reasonable to consider surgical ablation and LAA exclusion only in selected patients in whom anticipated success is high (eg, small left atrial dimension) and the risk–benefit ratio favors the additional intervention. Left atrial access during concomitant mitral valve procedures provides an opportunity to intervene when appropriate. It is important to adopt effective but safe techniques that minimize the chance of pacemaker requirement.

Ventricular dysrhythmias. Although revascularization can effectively treat ischemia-associated ventricular rhythm disturbances, ventricular tachycardia (VT) is a major cause of reduced quality of life and sudden cardiac death in patients with LV aneurysm secondary to transmural myocardial infarction.¹⁰³ The substrate for VT is usually located in the aneurysm’s border zone. Catheter ablation for aneurysm-related VT can be challenging. VT may be non-inducible or multifocal, and surgical treatment can be achieved with aneurysm resection and ablation at the time of CABG.

Epicardial lead placement. Data on concomitant epicardial defibrillator or cardiac resynchronization therapy (CRT) at the time of CABG are limited. Patients who meet guideline indications for implantable devices typically receive them through a transvenous approach if the indications persist after surgery.

TABLE 7. Factors influencing decisions about mitral valve surgery

Concomitant mitral valve surgery*
Factor 1: Presence of both viability and ischemia in the posterolateral wall
Factor 2: Graftability of posterolateral coronary artery targets
Factor 3: Presence of atrial arrhythmias, left atrial dilatation, organic mitral valve disease, and/or severe left ventricular dilatation
Factor 4: Heart failure symptoms predominate
Mitral valve repair vs replacement
Mitral valve replacement is associated with reduced recurrent MR in patients with severe ischemic MR.
Presence of basal aneurysm/dyskinesis is associated with recurrent MR after mitral valve repair. Other potential predictors include significant leaflet tethering and/or severe left ventricular dilatation (end-diastolic dimension >6.5 cm)

MR, Mitral regurgitation. *Factors 1 and 2 may support a conservative coronary artery bypass graft-alone approach, Factors 3 and 4 a more aggressive coronary artery bypass graft + mitral valve surgery approach.

TABLE 8. Other concomitant procedures

COR	LOE	Recommendations
Ia	B-R	Concomitant surgical ventricular restoration should be considered for patients with a true left ventricular aneurysm
Iib	B-R	Epicardial left ventricular lead implantation for future CRT use may be considered at the time of coronary artery bypass grafting in patients with QRS \geq 120 ms and LBBB or in patients likely to require chronic ventricular pacing
Iib	B-NR	Concomitant surgical ablation and left atrial appendage closure is reasonable in select patients with atrial fibrillation

COR, Class of recommendation; LOE, level of evidence; R, randomized; CRT, cardiac resynchronization therapy; LBBB, left bundle branch block; NR, nonrandomized.

CABG decreases the risk of sudden cardiac death in patients with CAD and ICM.¹⁰⁴ In the Multicenter Automatic Defibrillator Implantation Trial II¹⁰⁵ and Sudden Cardiac Death in Heart Failure Trial studies,¹⁰⁶ efficacy of ICDs was reduced if revascularization was performed before implantation, suggesting a protective effect of revascularization. For this reason, a 90-day waiting period after revascularization is recommended before proceeding with ICD implantation.^{10,107} Use of LifeVest (Zoll Medical, Pittsburgh, Pa) in this instance is a COR Iib, LOE B-NR recommendation in the 2017 AHA/ACC/Heart Rhythm Society Guideline for Management of Patients with Ventricular Arrhythmias and the Prevention of Sudden Cardiac Death.¹⁰⁸

Presence of severe LV dyssynchrony is associated with poor clinical outcomes despite revascularization.¹⁰⁹ The Cardiac Resynchronization Therapy Combined with Coronary Artery Bypass Grafting in Ischemic Heart Failure Patients (RESCUE) study demonstrated that in patients in NYHA class III or IV and LVEF \leq 35%, evidence of dyssynchrony (based either on QRS duration of more than 120 ms or tissue Doppler dyssynchrony), the concomitant CRT group had improved postoperative LV function and short-term outcomes compared with the CABG-alone group.¹¹⁰ The RESCUE follow-up study, with a mean follow-up of 55 months, associated concomitant CABG and CRT with reduced risk of both all-cause mortality (HR, 0.43; 95% CI, 0.23-0.84; $P = .012$) and cardiac death (HR, 0.39; 95% CI, 0.21-0.72; $P = .002$).¹¹¹ A smaller RCT including patients undergoing aortic valve replacement did not show a difference in the primary outcome of quality of life between the CRT and surgery-only groups.¹¹² There was, however, a 30-day mortality advantage in the CRT group. Thus, it is reasonable to consider concomitant CRT at the time of CABG in select cases (LVEF \leq 35%, evidence

of dyssynchrony), understanding the limited evidence in that setting.

Advanced HF Therapies as First-Line Therapy (Tables 9 and 10)

Although good outcomes can be achieved with CABG,¹¹³ some patients with ICM and advanced HF symptoms have high-risk anatomic and physiologic features that place them at prohibitive risk for, or unlikely benefit from, CABG. They may be better suited for percutaneous interventions, durable VAD therapy, or cardiac transplant.

One single-center study reported that poor coronary vessel quality was strongly predictive of perioperative death.¹¹⁴ Others have looked at a mix of conventional cardiac procedures in patients with severe LV dysfunction and identified LVEF \leq 25% before cardiac surgery and/or NYHA class IV symptoms, particularly in those aged \geq 70 years, as predictors of poor survival.¹¹⁵ Other predictors of poor survival in HF patients in general include RV dysfunction, inotropic dependency, greater LV volume, and end-organ dysfunction (see Figure 1).^{92,116,117}

With outcomes of durable VAD therapy¹¹⁸ and heart transplantation¹¹⁹ improving over time, high-risk ICM patients predicted to do poorly with CABG (Table 10) should be evaluated thoroughly to determine whether they qualify for advanced HF therapies.

NOTABLE ASPECTS OF INTRAOPERATIVE AND IMMEDIATE POSTSURGICAL CARE (Tables 11-13)

Because of the increased risk associated with operating on patients with ICM, especially those with advanced HF and high-risk features (see Preoperative Optimization and Perioperative Temporary Mechanical Support Section and Advanced HF Therapies as First-line Therapy Section), it is important that patient care be conducted by an

TABLE 9. Advanced surgical therapies instead of coronary artery bypass grafting

COR	LOE	Recommendations
IIa	B-NR	Advanced surgical therapies such as LVAD insertion or heart transplantation can be considered as alternatives to CABG for patients in NYHA functional class IV who have predictors of poor heart failure survival (see Table 10)
IIa	C-LD	Advanced surgical therapies such as LVAD insertion or heart transplantation can be considered as alternatives to CABG for patients in NYHA functional class IV who are anatomically high risk for CABG (see Table 10)

COR, Class of recommendation; LOE, level of evidence; NR, nonrandomized; LVAD, left ventricular assist device; CABG, coronary artery bypass grafting; NYHA, New York Heart Association; LD, limited data.

experienced multidisciplinary team led by the surgeon. Dedicated cardiac anesthesia specialists, experts in transesophageal echocardiography, and perfusion teams familiar with perfusing HF patients and managing MCS devices are essential. Adequate planning, including contingencies to address potential complications, should be part of the standard preoperative operating room huddle.

Standard cardiovascular critical care therapies are recommended, with the goal of maintaining a cardiac index >2.0 L/min/m², adequate organ perfusion and oxygen

delivery, and avoiding acidosis. In addition, the following aspects of care are particularly relevant to caring for patients with ICM and HF.

RV Management

Frequently, perioperative management of patients with low LVEF centers on the RV. For isolated RV dysfunction unresponsive to inotropic support, a temporary RV assist device may be considered. If the dysfunction is associated with severe respiratory compromise, an oxygenator may be added to the RV support circuit, or veno-arterial extracorporeal membrane oxygenation (VA-ECMO) can be instituted. In addition to meticulous myocardial protection during surgery, the following tenets underlie successful prevention and management of RV dysfunction in the setting of low cardiac output.^{120,121}

Avoiding hypoxic pulmonary vasoconstriction. To date, no RCTs have looked at outcomes in patients with RV dysfunction exposed to hypoxic versus normoxic alveolar ventilation. Nevertheless, the basic science is clear—alveolar hypoxia leads to pulmonary vasoconstriction. For example, in 1 study patients underwent isolated, single-lung hypoxic ventilation just before lung surgery via dual-lumen endotracheal intubation.¹²² During the hypoxic challenge to 1 of the lungs, flow to that lung virtually halved, mean arterial pressure increased by 50%, and pulmonary vascular resistance increased 3-fold.

Avoiding acidosis-driven pulmonary vascular resistance. Both respiratory acidosis¹²³ and metabolic acidosis¹²⁴ increase pulmonary vascular resistance, whereas alkalosis lowers it. Furthermore, acidosis potentiates the hypoxic pulmonary vasoconstrictor response. Thus, aiming for a pH in the alkalotic range is a crucial tool in decreasing pulmonary vascular resistance and RV afterload in the failing right heart.

TABLE 10. Predictors of poor outcomes after coronary artery bypass grafting in patients with heart failure

Predictors of poor heart failure survival
Intolerance to optimal guideline-directed medical therapy
Increasing diuretic requirement or diuretic resistant
Frequent hospitalizations
Peak VO ₂ <14 mL/kg/min or <50% of predicted
Inotrope dependency
Mechanical circulatory support to maintain adequate organ perfusion
Liver dysfunction
Creatinine >1.8 mg/dL
Cardiac index <2 L/min/m ²
Central venous pressure >20 mm Hg
Cardiac cachexia
Right ventricular dysfunction
Moderate or severe tricuspid regurgitation
Severely dilated ventricle
Degree of ventricular dysfunction out of proportion to ischemic burden
Large scar burden with limited myocardial viability
Anatomic risk
Poor coronary targets
Poor bypass conduits
Hostile mediastinum/anticipated difficult reoperation

VO₂, Maximum rate of oxygen consumption.

TABLE 11. Aspects of postoperative management

COR	LOE	Recommendations
I	C-EO	Protocols and resources should be in place for timely rescue from complications to optimize outcomes
I	C-LD	Postoperative hypoxemia, acidosis, volume overload, and elevated intrathoracic pressure should be avoided/corrected, particularly in patients with right ventricular dysfunction, because such patients are vulnerable to the detrimental hemodynamic influence of these conditions
IIa	B-R	In patients with prolonged QRS, pacing to accomplish biventricular synchrony can be helpful
IIa	C-LD	Atrial or AV sequential pacing is preferable to univentricular right ventricular pacing
IIa	C-LD	In patients with right ventricular failure or pulmonary hypertension, administration of inhaled nitric oxide or inhaled epoprostenol can help lower pulmonary vascular resistance

COR, Class of recommendation; LOE, level of evidence; EO, expert opinion; LD, limited data; R, randomized; AV, atrioventricular.

Avoiding elevated intrathoracic pressure. Increases in intrathoracic pressure directly increase pulmonary vascular resistance.¹²⁵ Therefore, pulmonary failure in the face of RV failure can create a conundrum. Although permissive hypercapnia decreases barotrauma and intrathoracic pressure, the respiratory acidosis that results causes pulmonary vasoconstriction and increases RV afterload. In instances of respiratory insufficiency in which RV failure is significant, VA-ECMO is an attractive option.

Use of inhalational agents—inhaled nitric oxide and prostacyclin. In the face of reactive pulmonary hypertension, inhaled nitric oxide or nebulized, synthetic prostacyclin (eg, epoprostenol) can effectively lower pulmonary vascular resistance without a significant effect on systemic

vascular resistance. In heart transplant patients,^{126,127} both of these inhalational agents significantly and similarly lower pulmonary vascular resistance. In a series of more than 120 open-heart surgery patients, De Wet and colleagues¹²⁸ showed that in those with pulmonary hypertension, inhaled prostacyclin decreased pulmonary vascular resistance by 25%, and in those with RV dysfunction, cardiac output increased by 30% to 35%.

Optimizing volume status. Invasive and noninvasive monitoring are critical to ensure appropriate loading of the RV.¹²⁹ Judicious volume administration to treat hypovolemia and diuretics or dialysis to treat fluid overload are used as needed. Importantly, a downward spiral of RV overfilling and RV failure should be avoided.

TABLE 12. Postoperative mechanical support

COR	LOE	Recommendations
I	B-NR	Patients exhibiting postcardiotomy shock or labile hemodynamic status should be considered for an intra-aortic balloon pump
IIb	C-LD	Patients exhibiting postcardiotomy shock or labile hemodynamic status may be considered for more advanced temporary mechanical support, especially if intra-aortic balloon pumping does not provide sufficient support

COR, Class of recommendation; LOE, level of evidence; NR, nonrandomized; LD, limited data.

TABLE 13. Mechanical support in the operating room and during the postoperative period

Mechanical support institution in operating room
Early institution is better than late to minimize end-organ hypoperfusion
Ensure suitable vascular access preoperatively
Avoid/address potential distal peripheral hypoperfusion
Criteria for institution
Preoperative indication (see Table 2)
Difficulty coming off-pump
Moderate or greater doses of inotropes to maintain cardiac index ≥ 2.0 L/min/m ²
Hypotension/evidence of end-organ hypoperfusion (eg, progressive acidosis/rising lactate) despite adequate resuscitation
Anticipated difficult postoperative course (eg, poor ventricular function despite revascularization, incomplete revascularization, and concerns about myocardial recovery)

Cardiac Pacing

Atrial versus atrial-RV versus RV pacing. Investigating the contribution of cardiac output at varying heart rates in non-surgical patients with emphysema and cor pulmonale or rheumatic heart disease, Samet and colleagues¹³⁰ found that compared with atrial pacing, RV pacing lowered cardiac output significantly, by roughly 20%. Hartzler and colleagues¹³¹ demonstrated that within 12 hours after surgery, atrial or atrial-RV pacing was always better than RV pacing alone, and furthermore, in patients with first-degree heart block, optimizing the atrioventricular node interval with atrial-RV pacing improved cardiac output compared with atrial pacing alone.

In a nonsurgical cohort retrospectively analyzing echocardiograms in patients with and without pulmonary hypertension, Sivak and colleagues¹³² showed that passive right atrial emptying, normally 65% before atrial contraction, dropped to 35% in the pulmonary hypertension cohort. Furthermore, active right atrial contraction accounted for 40% of RV stroke volume compared with 10% in the face of normal pulmonary arterial pressures. The implications for right atrial-RV synchrony in patients with poor RV ejection fraction and pulmonary hypertension are clear.

Ventricular resynchronization with biventricular pacing. Cannesson and colleagues¹³³ showed that in post-CABG patients, by placing V wires not only on the RV but also on the LV base, they were able to biventricular pace simultaneously, eliminating the obligatory intraventricular conduction delay associated with RV pacing. Even more pertinent, Weisse and colleagues¹³⁴ showed that in postoperative patients with low LVEF (mean, 30%) and left bundle branch block, right atrial-biventricular pacing and right atrial-LV pacing both eliminated left bundle branch block and LV dyssynchrony and significantly improved cardiac output compared with right atrial-RV pacing. Favorable outcomes were achieved with biventricular pacing when CRT epicardial leads were placed at the time of CABG (see [SVR Section](#)).^{110,112}

Postcardiotomy Shock and Temporary MCS (Tables 12 and 13)

In the face of postcardiotomy shock (PCS) with inability to separate from cardiopulmonary bypass or requirement for high-dose inotropic therapy, MCS should be considered.¹³⁵ Table 5 summarizes key features relating to MCS use during the intraoperative and postoperative periods.

IABP. Although there are no RCTs for PCS, or even retrospective comparisons, IABP use has been considered first-line therapy for both medical shock and PCS.¹³⁶⁻¹³⁸ Its safety and ease of placement make it the most attractive of the MCS devices. Even if the hemodynamic support provided by an IABP is insufficient in reversing cardiogenic shock, its usefulness in conjunction with ECMO¹³⁹ argues for it as the initial mode of support. However, the data do not support its use as an adjunct to an Impella device (Abiomed, Danvers, Mass).¹⁴⁰

Historically, mortality associated with an IABP was roughly 50% when used in PCS.^{138,141} More recently, in an analysis of 4550 patients operated on between 2004 and 2008, 5% required an intraoperative or postoperative IABP, with overall mortality of 37%.¹⁴² For patients exhibiting predominantly right-sided failure, an IABP was equally effective, with an increase in cardiac index of 50% and associated mortality of 31%. This study specifically addressed the issue of IABP effectiveness in both right- and left-sided failure.

Impella. The past decade has seen the emergence of percutaneous or surgically implanted axial-flow devices for all types of cardiogenic shock, including PCS. Unlike the IABP, these devices drastically reduce LV end-diastolic pressure and volume and may be better poised to support systemic perfusion while allowing the heart to recover. Engström and colleagues¹⁴³ reported on 46 patients with PCS treated with the Impella 5.0, mostly after CABG, at 3 European centers. Roughly half received an IABP before the Impella device was placed. Overall survival was 40% at 30 days. More recently, David and colleagues¹⁴⁴ reported on use of the Impella 5.0/Impella LD in 29 patients (40% with isolated CABG) treated for PCS between 2010 and

2015. Mortality was approximately 40%, similar to the aforementioned study and to results seen with IABP use in these situations. The best results for PCS treatment were reported by Griffith and colleagues¹⁴⁵ in the RECOVER I study, wherein an Impella 5.0 was placed in 16 patients having difficulty weaning from cardiopulmonary bypass. Fifteen were successfully supported, with 30-day survival of 94%, but enthusiasm regarding this outcome must be colored by the low level of inotropic support required by the study protocol before Impella placement.

The 2 RCTs examining the efficacy of the Impella were in acutely ischemic medical patients, comparing its outcomes with those of an IABP.^{146,147} No difference was found between the therapies.

ECMO. Use of ECMO for PCS has been well described in a recent study.¹³⁵ There are no RCTs regarding its effectiveness in PCS, but a wealth of retrospective studies show that in this setting, mortality ranges from 60% to 70%.¹⁴⁸⁻¹⁵⁰ In a more recent report of the European registry of close to 700 patients, including a systematic review and meta-analysis of nearly 2500 patients,¹⁵¹ mortality was 43% to 75% with the universal, concomitant use of an IABP in many centers. In that study, switching to peripheral cannulation appeared to provide close to a 10% mortality benefit. Finally, ECMO with LV unloading appears to provide a 10% to 20% mortality benefit in 2 recent studies—a multicenter study wherein LV unloading was accomplished with an Impella device in medical patients in cardiogenic shock,¹⁵² and a meta-analysis of a mixed medical/PCS population predominantly unloaded with an IABP.¹⁵³

POSTDISCHARGE MANAGEMENT (Table 14)

The importance of adhering to guideline-directed medical therapy (GDMT), secondary prevention, and cardiac rehabilitation cannot be overemphasized.^{12,154} Close follow-up is recommended for titration of HF medications and continued assessment and evaluation for needed additional interventions, including device implantation (eg, ICD/CRT)¹⁴ or advanced HF surgical therapies.

A well-recognized vulnerable period, typically defined as 90 days postdischarge, is associated with a several-fold increase in HF-associated rehospitalization and mortality. Thus, post-CABG patients with HF should undergo close clinical monitoring and follow-up. Early (7-14 days) postdischarge follow-up to review volume status and titrate guideline-directed medications upward is associated with better short-term outcomes.¹⁵⁵

Although studies directly evaluating and comparing the impact of GDMT on HF patients with reduced LVEF (HFrEF) who have or have not undergone CABG are limited, conventional medical opinion supports that GDMT goals for CABG patients should not differ from those for patients with CAD and HFrEF. Additionally,

post hoc analyses reveal that the best long-term outcomes are achieved by patients who are maintained on optimal medical therapy.¹⁵⁶

Consensus statements define GDMT for HFrEF patients to include the following¹¹: renin-angiotensin system inhibitors, such as an angiotensin-converting enzyme inhibitor, angiotensin type II receptor blocker, or an angiotensin receptor neprilysin inhibitor; a beta-blocker; and a mineralocorticoid receptor antagonist, such as spironolactone or eplerenone. Among renin-angiotensin system inhibitors, RCTs support the preferential use of an angiotensin-receptor neprilysin inhibitor to reduce long-term morbidity and mortality as well as post-discharge hospitalization.^{157,158}

Recent strong evidence from several large RCTs of HFrEF patients without regard to diabetes status is likely to expand GDMT to include sodium-glucose cotransporter 2 inhibitors.^{159,160}

The choice of antiplatelets and/or anticoagulants follows standard guidance for post-CABG patients. Convincing data to initiate anticoagulants in HFrEF patients without an indication for AF or known LV thrombus are not available. Among CABG patients who have undergone a concomitant ventricular procedure, a short course of anticoagulation may be desirable, although absent comparative studies, the type and duration remains dependent on local experience and patient-related factors.

PROGRAM CHARACTERISTICS AND QUALITY INDICATORS (Table 15)

Management of patients with ICM and HF is complex and often involves multidisciplinary input, from patient workup to treatment strategy to long-term follow-up. This entails a comprehensive and specialized program dedicated to the acute and chronic care needs unique to this patient population, with appropriate care protocols in place. In addition to surgical expertise in CABG, expertise in adjunct cardiac procedures, such as valve repair or replacement, SVR, and MCS, are essential qualifications in the surgical care of patients with advanced ICM and HF.

Some data suggest that the number needed to treat at higher-volume hospitals to avoid 1 death is greater for low-risk CABG (<2% in-hospital mortality) than higher risk CABG.¹⁶¹ In addition to the importance of volume in maintaining the surgeon's technical competency and readiness of the surgical team, volume is also a structural metric that correlates with process measures that are important determinants of outcomes of patients with HF.¹⁶² Indeed, an infrastructure is recommended that supports multidisciplinary HF care delivery similar to that needed for a durable VAD program.

Regarding risk assessment, advanced degrees of ventricular dysfunction and HF are important predictors of CABG operative mortality.^{35,163} In addition, patients with HF often

TABLE 14. Postdischarge management

COR	LOE	Recommendations
I	C-EO	Close follow-up of patients by a multidisciplinary heart team for appropriate adjustments of heart failure medications and implementation of other guideline-directed therapies as indicated
I	B-NR	Referral for CRT with or without ICD implantation should be considered after CABG in patients with QRS ≥150 ms, LVEF ≤35% at 90 days after revascularization per professional guidelines

COR, Class of recommendation; *LOE*, level of evidence; *EO*, expert opinion; *NR*, nonrandomized; *CRT*, cardiac resynchronization therapy; *ICD*, implantable cardioverter-defibrillator; *CABG*, coronary artery bypass grafting; *LVEF*, left ventricular ejection fraction.

present with renal insufficiency, respiratory insufficiency, and hepatic dysfunction, all of which are independently associated with increased operative morbidity and mortality. Traditional risk models may underestimate surgical risk¹⁶⁴ by not capturing or accurately adjusting for physiologic and anatomic risk factors that affect patient outcomes. For example, patient frailty, quality of target vessels, degree of RV dysfunction, degree of myocardial remodeling, and extent of myocardial viability are all recognized by surgeons as important risk factors, but they are not included in—and thus fly under the radar of—current risk models.

Patients deemed appropriate candidates for CABG combined with planned insertion of a temporary MCS device as a bridge to recovery or to long-term MCS/heart transplantation, if needed, should be tracked as a separate cohort and excluded from the isolated CABG category for purposes of quality assignment. Hence, centers with the necessary infrastructure and expertise to handle such complex cases could care for high-risk referrals from other less-equipped centers without risking lower public ratings, yet still be monitored for performance.

In addition to the standard CABG and valve surgery quality metrics of risk-adjusted perioperative morbidity and mortality, it is recommended that report cards include longer-term outcomes and indicators of case-mix complexity and risk that are hard to quantify and adjust for when including the percentage of transfers from other cardiac surgery centers.

FUTURE DIRECTIONS AND GAPS IN KNOWLEDGE

The field of MCS has evolved rapidly during recent years, and its role in managing patients with ICM and HF is likely to grow. It is expected that the safety of MCS devices will improve and the timing and indication for their use will be fine-tuned. The time is ripe for randomized trials

investigating the perioperative role of new temporary MCS devices and comparing durable MCS versus surgical revascularization with or without temporary MCS in certain high-risk patients with ICM and HF. RV support has always been a challenge and continues to be a target for improvement.

As discussed in the [Revascularization Modalities](#) Section, the relative role of PCI and CABG in the context of improved medical therapies needs more clarity, perhaps in the context of more nuanced imaging and other clinical prognosticators.

Much progress has been made in the transcatheter valve intervention arena, especially for functional MR.^{89,165,166} Transcatheter therapies, in addition to their role in treating

TABLE 15. Key characteristics and quality indicators to report: Center level

Case category
Isolated CABG
CABG combined with valve surgery
CABG combined with planned temporary VAD
Volume
Percentage of patients with LVEF ≤35% and LVEF <25%
Percentage of cardiac reoperations
Percentage of patients transferred from other cardiac surgery centers
Certified VAD center (Yes/No)
Risk-adjusted operative mortality
Risk-adjusted operative morbidity (stroke, new dialysis, mediastinitis, reoperation, perioperative myocardial infarction)
1-year patient survival
Participation in a national cardiac surgery quality program (Yes/No)
Open access to outcome information and patient satisfaction surveys (Yes/No)

CABG, Coronary artery bypass grafting; *VAD*, ventricular assist device; *LVEF*, left ventricular ejection fraction.

patients who are not candidates for open surgery, can play a complementary role in treating post-CABG patients who develop worsening valvular disease. Longer-term data are needed in this area.

The role of biomarkers in the diagnostic and prognostic domains is evolving. In addition to natriuretic peptides and troponins, multiple other biomarkers, including those of inflammation, oxidative stress, vascular dysfunction, and myocardial and matrix remodeling, are being evaluated as promising tools in managing HF.¹¹ Their role in guiding preoperative optimization and postoperative surveillance and follow-up remains to be defined.

Despite promising preclinical data, application of stem cells to the treatment of patients with HF has not been shown to improve clinical outcomes and for now should be considered experimental.¹⁶⁷ Other areas of innovation include state-of-the-art wireless monitoring and surveillance, and cardiac contractility modulation, some already in clinical use.¹⁶⁸

Conflict of Interest Statement

Dr Bozkurt is an advisor with Abbott Vascular and Liva-Nova and a consultant with scPharmaceuticals, Amgen, Baxter, Bristol Myers Squibb, Relaysa/Vifor Pharma, Respicardia, and Sanofi-Aventis. Dr Chikwe has received institutional or other benefits from Edwards and Abbott. Dr Moon has been a consultant for Edwards and Medtronic. Dr McCarthy has been a speaker for Medtronic, Atricure, and Edwards Lifescience and has conducted research for the REPAIR-MR trial. Dr Puskas has been a consultant for Medtronic, Medistim, VGS, and Scanlan. Dr Ruel has been a consultant and conducted research for Medtronic. Dr Silvestri has been a consultant for Abbott, Medtronic, and Syncardia. Dr Slaughter has been a consultant for Medtronic and a speaker for Abbott. Dr Soltesz has been a consultant for Abiomed and Abbott. Dr Taggart has been a consultant and a speaker, conducted research, and received institutional or other benefit from Medtronic, Medistim, and VGS as well as having share ownership in VGS. All other others reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

American Association for Thoracic Surgery Cardiac Clinical Practice Standards Committee Members include Faisal G. Bakaean, MD (Co-Chair), S. Chris Malaisrie, MD (Co-Chair), Leonard N. Girardi, MD (Director), Joanna Chikwe, MD, Mario Gaudino, MD, MSCE, and Wilson Szeto, MD.

Invited expert reviewers include: *Cardiology*: Deepak Bhatt, MD, Jerry Estep, MD, and Roxana Mehran, MD; *Surgery*:

Hirukuni Arai, MD, Daniel Goldstein, MD, Walter J. Gomes, MD, PhD, Michael Halkos, MD, Ki-Bong Kim, MD, Craig Selzman, MD, Nicholas G. Smedira, MD, Miguel Sousa Uva, MD, Lars G. Svensson, MD, PhD, James Tatoulis, MD, Michael Z. Tong, MD, and Marco Zenati, MD; and *Electrophysiology*: Bruce Wilkoff, MD.

The authors thank Hiba Ghandour, MD, for manuscript preparation, Tess Parry for editorial assistance, Michelle Demetres for literature search, and Lori Burrows for administrative support.

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Key Words: CABG, heart failure, ischemic cardiomyopathy, expert consensus, guidelines, mitral regurgitation, ventricular assist device, intra-aortic balloon pump, perioperative care, surgical ventricular restoration, ventricular remodeling, coronary artery disease, coronary artery bypass grafting

TABLE E1. Literature search strategy, including search terms and associated results

Search step	Search terms and logic	References retrieved
1	Heart failure/	119,024
2	(heart failure or cardiac failure or heart decompensation or cardiac decompensation or myocardial failure or failing heart or heart backward failure or cardiac incompetence or cardiac insufficiency or cardiac stand still or cardiac decompensation or cardiac insufficiency or cardiac failure or decompensation cardiac or heart incompetence or heart insufficiency or insufficientia cardis or myocardial insufficiency or myocardial decompensation).tw.	183,469
3	(low ventricular ejection fraction* or low ejection fraction* or left systolic dysfunction* or left ventricular systolic dysfunction*).tw.	4120
4	(ejection fraction adj2 (less than 40 or "less than 40%" or "< 40" or "< 40%")).tw.	2238
5	or/1-5	218,005
6	Coronary artery bypass/or coronary artery bypass, off-pump/	51,510
7	(coronary adj2 (bypass* or graft* or surger*)).tw.	51,993
8	(CABG or aortocoronary anastomosis or total arterial revasculari*ation* or multiple arterial revasculari*ation*).tw.	18,144
9	Internal mammary–coronary artery anastomosis/	2318
10	((right internal mammary artery or RIMA or left internal mammary artery or LIMA or Coronary Internal Mammary Artery or arteria mammaria interna or arteria thoracica interna or internal thoracic artery or mammary internal artery) and (transplant* or graft* or anastomosis)).tw.	4136
11	(surgical revasculari*ation* or cardiac muscle revasculari*ation* or coronary revasculari*ation* or heart muscle revasculari*ation* or heart myocardium revasculari*ation* or heart revasculari*ation* or internal mammary arterial anastomosis or internal mammary arterial implant* or internal mammary artery anastomosis or internal mammary artery graft* or internal mammary artery implant* or internal mammary-coronary artery anastomosis).tw.	11,684
12	Myocardial revascularization/	11,104
13	(myocardial revasculari*ation* or myocardium revasculari*ation* or mammary artery implant* or mammary arterial implant* or mammary artery reimplant* or mammary arterial reimplant* or vineberg operation*).tw.	5016
14	or/6-13	87,289
15	5 and 14	6381
16	limit 15 to (english language and yr="2010 -Current")	2321

a. Details of Medline search. b. Results of 3 database searches: Medline: 2303, Embase: 4544, Cochrane: 333. Total: 7180.