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Management Strategies for High-Risk Cardiac Surgery: Improving Outcomes in Patients with Heart Failure

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ABSTRACT

Background: Surgical heart failure management is the fastest growing aspect of cardiovascular surgery. Advances in cardiac surgical techniques have changed the number and types of operations permitted physicians and thus broadened the complexity of patients recommended for operation.

Methods: Surgeons, anesthesiologists and cardiologists face hemodynamic and pathophysiological challenges that can be optimally overcome only by modifying treatment strategies. Because many treatment standards are still evolving in this rapidly advancing field, a team of cardiovascular surgeons and anesthesiologists convened to share clinical experience and impressions and discuss practical issues related to high-risk patients undergoing heart surgery.

Results: Heart failure pathophysiology, surgical heart failure management, including mitral reconstruction and left ventricular remodeling, cardiopulmonary bypass weaning, inotropic support, transesophageal echocardiography and acute cardiovascular collapse after cardiac surgery are discussed.

Conclusion: This article is intended to guide clinicians to improve patient care and outcomes in this special population by providing specific guidance on the appropriate use of inotropic and mechanical support in patients undergoing high-risk procedures using innovative techniques.

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INTRODUCTION

Advances in cardiac surgical techniques have changed the number and types of operations permitted physicians and thus broadened the complexity of patients recommended for operation. Not only has the overall number of individuals undergoing elective cardiac surgery since the early 1980s increased, but today's patients are also proportionately older and at higher risk [Warner 1997]. Among patients undergoing major vascular surgery, cardiovascular complications are the most important causes of perioperative morbidity and mortality [Poldermans 1999], and patients with advanced heart failure have the highest risk for perioperative events and decreased survival [Ferraris 1998]. Continued improvements in combined medical and surgical approaches [Christenson 1997, McCarthy 1997, Smedira 1997, Bolling 1998, Goldstein 1998, McCarthy 1998, Beck 1999, Körfer 1999, Kuhn 2000] together with novel postoperative monitoring techniques [Ninomiya 1997, Savage 1997, Savage 1999, Shanewise 1999] are enabling patients with advanced heart failure to receive surgical therapy in an attempt to improve cardiac function and survival [Warner 1997, Dalrymple-Hay 1999, McCarthy 1999, Nashef 1999].

Finally, surgical heart failure management is the fastest growing aspect of cardiovascular surgery. Surgeons, anesthesiologists and cardiologists face hemodynamic and physiological challenges that can be optimally overcome only by modifying treatment strategies. Because many treatment standards are still evolving in this rapidly advancing field, an expert panel was convened to review contemporary treatment strategies in the high-risk cardiac surgical patient. This article reviews cutting edge approaches to the management of patients with compromised ventricular function using pharmacological and mechanical means.

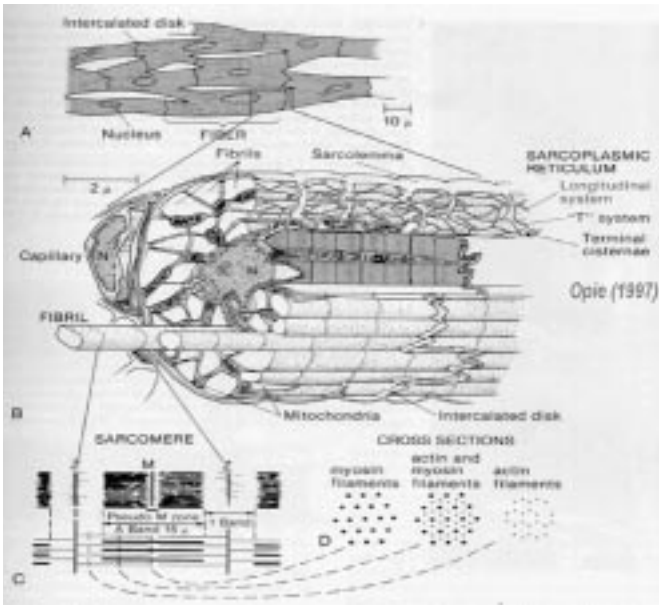

Figure 1. Myocardial cell structure. (Adapted with permission from Opie LH [Opie 1997]).

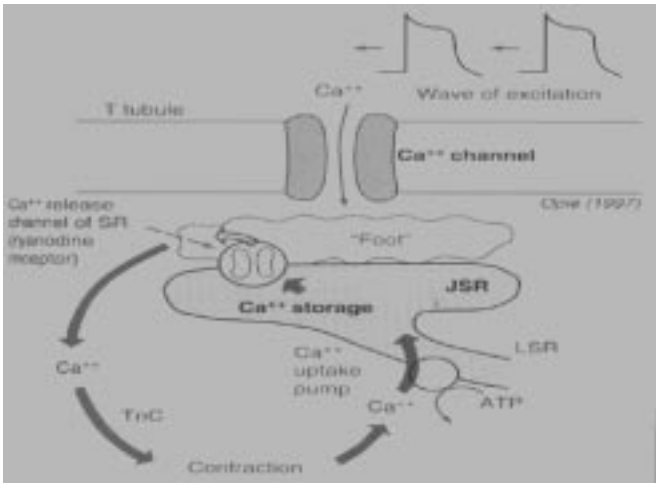

Figure 2. Myocardial function with action-potential activation. (Reprinted with permission from Opie LH [Opie 1997]).

DISCUSSION

Heart Failure

Despite significant advances in the management of cardiovascular diseases, heart failure prevalence has been increasing [Gheorghiade 1998, American Heart Association 1999], mainly because the age of the population is also increasing [Ho 1993]. Heart failure afflicts approximately four to five million individuals in the United States at an annual cost in excess of $12 billion [Levit 1991, O'Connell 1994]. Clinical estimates suggest that approximately 5% of patients with heart failure are New York Heart Association (NYHA) Class IV patients [Adams, Jr. 1998].

Definition and Classification

Heart failure is the term used to characterize the pathophysiological condition in which the heart cannot pump blood at a rate sufficient to meet the metabolic requirements of the tissues or can do so only from elevated filling pressures [Lenfant 1994, Colucci 1997]. Heart failure is usually the result of "primary" myocardial failure. However, an indistinguishable syndrome may occur with normal myocardial function and excessively deranged loading conditions.

The pathophysiological definition of heart failure implies that it can be caused by abnormalities in systolic or diastolic function. Systolic heart failure is the inability of the active contractile phase of the cardiac cycle to meet the body's metabolic demands, whereas diastolic heart failure is the condition where the heart cannot sustain an adequate preload volume for the maintenance of normal systolic function. This may be associated with normal or inadequate cardiac output [Gaasch 1994]. Clinical manifestations of heart failure are due to inadequate cardiac output and/or damming up of blood behind one or both ventricles (i.e., the forward or backward pressure theories of heart failure). Implicit in the backward failure theory is the idea that intravascular volume redistributes behind the specific cardiac chamber that is initially affected. Patients with left ventricular (LV) myocardial infarction (MI), hypertension and aortic and mitral valve disease initially manifest symptoms of pulmonary congestion (i.e., left heart failure). Over time, patients experience generalized fluid accumulation including ankle edema, congestive hepatomegaly, ascites and pleural effusion (i.e., right heart failure) [Little 1997].

Myocardial Cell Structure and Function

The contractile cells of the heart (cardiomyocytes), composed of myofibrils (actin and myosin), mitochondria, the sarcoplasmic reticulum (SR) and a centrally located nucleus, constitute 75% of the heart [Opie 1997]. Figure 1 (◎) shows myocardial cell structure [Opie 1997]; Figure 2 (◎) shows myocardial function with action-potential activation [Opie 1997].

A cell membrane (sarcolemma) surrounds the cell and invaginates into its interior as the t-tubule network. The mitochondria are responsible for energy generation (i.e., ATP) for contractile function and maintenance of transmembrane ion gradients. The SR is a fine network throughout the cell (parts of which lie in close proximity to the t-tubules) and is responsible for calcium (Ca^{++}) release into the cell during contraction and ATP-dependent uptake during relaxation. The myofibrils are composed of thin actin and thick myosin filaments. Myosin filaments are attached to the z-line by the protein titin, whereas actin filaments are attached directly. At regular intervals on the actin filaments are troponin complexes. These complexes are composed of troponin C, which binds Ca^{++} and then is able to bind the inhibitory protein troponin I. This repositions troponin m on the actin filament, which removes the inhibition exerted by

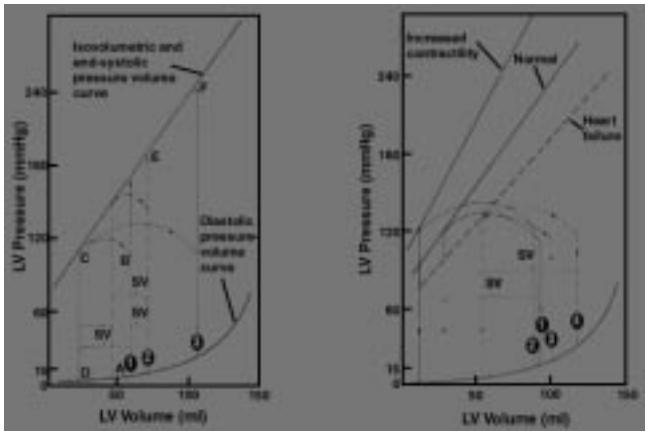

Figure 3. LV response to increased afterload, preload and contractility. (ESPVR = end-systolic pressure-volume relation; E_{ES} = slope of the end-systolic pressure-volume relation.) (Adapted with permission from Little WC and Braunwald E [Little 1997]).

tropomyosin on the actin-myosin interaction. ATP binds to the bridging myosin and weakens the binding state. With the inhibitory influence of troponin I once again dominating the actin-myosin interaction, the cross-bridging is inhibited. In the presence of calcium (Ca^{++}), the process occurs repetitively, and the actin moves more centrally along the myosin filament.

With action-potential activation of the sarcolemma, small amounts of Ca^{++} enter the cell, which results in a greater Ca^{++}-induced Ca^{++} release from the SR leading to a 10-fold Ca^{++} concentration increase and troponin C binds Ca^{++} forming a complex which inhibits troponin I. Beta receptors on the sarcolemma (t-tubules near SR Ca^{++} release channels) serve to open the Ca^{++} in addition to increasing the uptake of Ca^{++} into the SR. Ca^{++} is taken into the SR by a Ca^{++} pump that is ATP-dependent. Phospholamban is the protein receptor that, when phosphorylated, triggers the Ca^{++} uptake into the SR and storage with calsequestrin. Protein kinases, which provide the phosphyloration for phospholamban, are stimulated by cyclic adenosine monophosphate (cAMP [increased by beta stimulation]) and enhanced intracellular Ca^{++}. The sarcolemma Ca^{++} channels are voltage-gated and with beta stimulation there is a larger opening and more channels are open for increased Ca^{++} flux into the cell. Beta receptors on the sarcolemma convert an extracellular hormone or drug into an intracellular physiologic change via intermediary messengers (G-protein, cAMP and kinase A). With end-stage heart failure, the SR Ca^{++} release receptor, the Ca^{++} uptake pump and phospholambans are decreased. In addition, there is major down-regulation of the beta-1 receptor, beta-2 uncoupling from adenyl cyclase, diminished adenyl cyclase activity, and increased levels of the G_i protein, which inhibits the G_s protein that activates adenyl cyclase.

Contractile Performance

The cardiac cycle is composed of seven distinct phases: atrial contraction, isovolumetric contraction, rapid ejection, slowed ejection (protodiastole), isovolumetric relaxation, rapid ventricular filling and slowed ventricular filling (diastasis). The three major determinants of cardiac contractile performance are the Frank-Starling mechanism (preload and afterload), heart rate and the contractile state of the heart [Opie 1997]. Myocardial performance and its determinants may be easily visualized using pressure volume loops, which demonstrate the relation between preload, afterload, contractility and stroke volume (Figure 3, ◎) [Little 1997]. Increased afterload can decrease LV systolic emptying in the absence of myocardial contractility depression. Increased preload, if it occurs without a change in end-systolic pressure, results in a larger stroke volume. A primary increase in myocardial contractility effects a steeper ESPVR. If preload and afterload remain constant, an increase in stroke volume occurs.

Adaptive Mechanisms in Heart Failure

When the myocardium does not meet systemic metabolic demands, several adaptive mechanisms activate to maintain normal pumping function (Table 1, ◎) [Katz

Table 1. Adaptive Mechanisms in Heart Failure.

Response	Short-Term Effects	Long-Term Effects
Salt and water retention	Augments preload	Causes pulmonary congestion, anasarca
Vasoconstriction	Maintains blood pressure for perfusion of vital organs	Exacerbates pump dysfunction; increases cardiac energy expenditure
Sympathetic stimulation	Increases heart rate and ejection	Increases energy expenditure
Sympathetic desensitization	—	Spares energy
Hypertrophy	Unloads individual muscle fibers	Leads to deterioration and death of cardiac cells; cardiomyopathy of overload
Capillary deficit	—	Leads to energy starvation
Mitochondrial density	Increase in density helps meet energy demands	Decrease in density leads to energy starvation
Appearance of slow myosin	—	Increases force, decreases shortening velocity and contractility; is energy-sparing
Prolonged action potential	—	Increases contractility and energy expenditure
Decreased density of sarcoplasmic reticulum calcium-pump sites	—	Slows relaxation; may be energy-sparing
Increases collagen	May reduce dilatation	Impairs relaxation

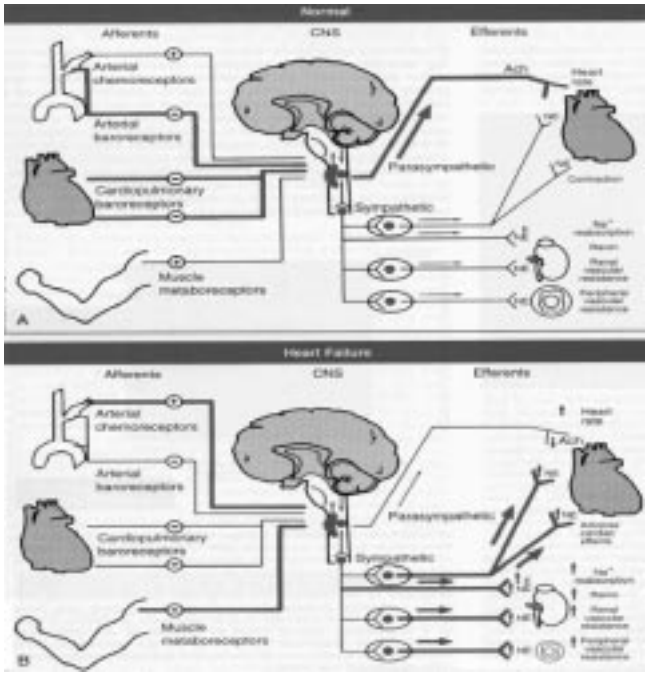

Figure 4. Mechanisms for generalized sympathetic activation and parasympathetic withdrawal in heart failure. A, under normal conditions; and B, with progression of heart failure. (Ach = acetylcholine; CNS = central nervous system; E = epinephrine; Na^+ = sodium, NE = norepinephrine.) (Reprinted with permission from Colucci W and Braunwald E [Colucci 1997]).

1990]. Most important among theses are the Frank-Starling mechanism, myocardial hypertrophy and activation of neurohumoral mechanisms [Katz 1990, Katz 1994]. With the onset of primary myocardial failure, the contractility curve of the Frank-Starling performance relation is shifted downward and to the right. To maintain adequate myocardial performance, the LV end-diastolic volume (EDV) increases (through diminished stroke volumes and central volume redistribution) with a resulting compensation in pump function maintaining output. As further deterioration in myocardial contractility occurs, a point is reached where cardiac pump function is only maintained in the presence of increased preload, which results in pulmonary congestion. With persistence of elevated loads, myocardial cells are stimulated. The resulting increase in mitochondria synthesis serves to meet the elevated energy demands in the failing heart. Eventually, persistence of this hemodynamic load results in cardiac hypertrophy with increased myocardial myofibrils and mitochondria. Unless the loading conditions are normalized, the ventricle eventually undergoes a remodeling process with myocardial cell necrosis, fibrosis and LV dilation.

In response to reduced cardiac output and elevated atrial pressures, a series of neurohumoral changes occurs, including increased sympathetic activation (with parasympathetic withdrawal), activation of the renin-angiotensin-aldosterone system and the elicitation of an inflammatory cytokine response [Francis 1984, Dzau 1987]. The activation of the sympathetic system occurs as a result of increased excitatory inflow from the arterial and cardiopulmonary baroreceptors. The overall response to sympathetic activation and withdrawal of parasympathetic tone is elevation of circulating catecholamine concentrations, primarily norepinephrine, with increased heart rate and excessive vasoconstriction, increased circulating renin concentrations and subsequent increased sodium reabsorption by the renal tubules (Figure 4, ◉) [Colucci 1997, Schrier 1999]. The elevation of circulating norepinephrine may result from a combination of increased release from nerve endings and consequent excess in plasma, and reduced uptake by adrenergic nerve endings. Patients with heart failure demonstrate increased adrenergic nerve outflow, and the level of nerve activity correlates with the concentration of plasma norepinephrine. The extent of elevation of plasma norepinephrine concentration correlates directly with the severity of the LV dysfunction [Colucci 1997]. In patients studied in the Studies on Left Ventricular Dysfunction (SOLVD) trial, plasma norepinephrine, renin activity, atrial natriuretic factor, and arginine vasopressin were elevated in patients with symptomatic heart failure [Francis 1990]. In addition, plasma angiotensin II concentration was significantly elevated, even in asymptomatic heart failure patients studied in SOLVD [Francis 1990]. Angiotensin II is a potent peripheral vasoconstrictor and contributes, along with increased adrenergic activity, to the excessive elevation of systemic vascular resistance in heart failure patients. Angiotensin II also enhances the adrenergic nervous system's release of norepinephrine. Several important mediators, including arginine vasopressin, natriuretic peptides, and endothelin, have important effects on the myocardium and vasculature and are involved in heart failure pathophysiology [Colucci 1997]. Inflammatory responses to heart failure also occur, including production of tumor necrosis factor (a direct myocardial depressant), interleukin 1B and other peptide growth factors, which induce further myocardial hypertrophy. The role of inflammatory cytokines in the pathophysiology of heart failure remains to be elucidated.

The primary goals of heart failure management are to improve quality of life, reduce the frequency of heart failure exacerbations and extend survival [Rich 1999]. To achieve these goals, optimal management requires surgical correction of the underlying cause whenever possible, prudent pharmacological support, and nonpharmacological and rehabilitative regimens of care.

Surgical Heart Failure Management: Selected Approaches

Heart transplantation is standard treatment for patients with severe congestive heart failure. The International Society for Heart and Lung Transplantation maintains a registry of heart transplantation. The number of transplantations reported to the registry per year (Figure 5, ◉) has plateaued since 1990 at approximately 3500 per year [Hunt 1998]. Because the procedure is limited both by the availability of donor hearts and its unsuitability in older patients or those with comorbid medical conditions [Hunt 1998], new surgical strategies to manage severe end-stage

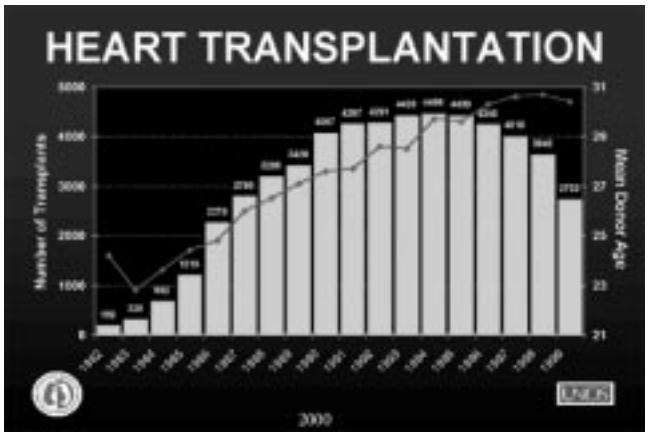

Figure 5. Number of heart transplantations performed internationally (green bars) and mean donor age (red line) per calendar year.

heart disease have evolved such as coronary artery revascularization, cardiomyoplasty, LV myoreduction surgery and mitral valve repair [McCarthy 1999].

Mitral Valve Annuloplasty

Functional mitral regurgitation (MR) is a significant complication of the ventricular dilation associated with advanced heart failure [Kono 1992] and a predictor of poor survival. Reported one-year mortality for such patients is between 46% and 70% [Stevenson 1987, Anguita 1993]. Historically, mitral valve replacement was the surgical approach to patients with MR. Little was understood about the adverse consequences that interrupted annulus-papillary muscle continuity had on LV systolic function [Pitarys 1990], and this procedure was associated with very high mortality rates [Phillips 1981, Pinson 1984]. The concept of an MR "pop-off" effect originated in this patient population. It was incorrectly thought that reversal of blood flow was beneficial to the heart failure patient. Subsequently, preservation of annulus-papillary muscle continuity has been demonstrated to be of paramount importance to LV function preservation [David 1983, Sarris 1988]. Preservation of the mitral valve apparatus and the LV in mitral valve repair enhances and maintains LV function and geometry with an associated decrease in wall stress [Goldman 1987, Tischler 1994]. This procedure has been shown to be safe, with a significant decrease in operative morbidity and mortality and good long-term outcomes [Gallino 1987, Rankin 1988, Akins 1994, Alvarez 1996]. Patient mortality from mitral valve replacement is ascribed to disruption of the subvalvar apparatus and loss of LV function. Maintenance of the chordal, annular, subvalvar continuity and mitral geometric relationships are essential to preserving overall ventricular function and may be even more crucial in patients with compromised LV function. MR in this patient cohort arises from a ventricular pathology; therefore, a solution directed at the mitral valve that encompasses the entire left ventricle would be ideal.

With this goal in mind, 92 patients with end-stage cardiomyopathy and refractory MR underwent mitral valve

Figure 6. Mitral valve repair with an undersized flexible annuloplasty ring.

repair with an undersized flexible annuloplasty ring (Figure 6, ◉) [Bolling 1998] at the University of Michigan from 1993 to 1999. Detailed methodology has been previously described [Bolling 1998]. All patients had severe LV systolic dysfunction (defined as an LV ejection fraction (LVEF) <25%) and NYHA Class III or IV heart failure despite receiving maximal medical therapy. Overall operative mortality was 5%. Five mortalities, including intraoperative death due to right ventricular failure (1), cardiac failure (1), stroke (1) and multisystem organ failure (2), were reported at 30 days. Five patients required intra-aortic balloon pump (IABP) support, and no patients required the use of an LV assist device (LVAD). The duration of follow-up has been 1-68 months (mean 38 months), with a one- and two-year actuarial survival of 80% and 70%, respectively. A total of 26 late deaths have occurred. At 24-month follow-up, all remaining patients are in NYHA Class I or II, with a mean LVEF of 26%. Interim results are presented in Table 2 (◉); however final results will soon be available. The NYHA class improved for each patient, and all patients reported subjective improvement in functional status. Improvement in LVEF, cardiac output and EDV was demonstrated for all patients with a reduction in sphericity index and regurgitant fraction. Although significant undersizing of the mitral annulus was employed to overcorrect for the zone of coaptation, no mitral stenosis was induced, nor was any systolic anterior motion (SAM) noted in this study. SAM was avoided because of the widening of the aorto-mitral angle and increased LV size seen in cardiomyopathic patients. Acute remodeling of the base of the heart from the undersizing of the mitral annular ring may contribute to the improvement seen in these myopathic hearts. This may reestablish the ellipsoid shape and somewhat normal geometry to the base of the LV

Table 2. Matched Preoperative and 24-Month Postoperative in 49 Patients Undergoing Mitral Reconstruction for Cardiomyopathy.

Hemodynamic Parameter	Preoperative	24-Month Postoperative
EDV (mL)	281 ± 86	206 ± 88*
Sphericity Index (D/L)	0.82 ± 0.10	0.74 ± 0.07*
EF (%)	16 ± 5	26 ± 8*
Forward Cardiac Output (L/min)	3.1 ± 1.0	5.2 ± 0.8*
Regurgitant Fraction (%)	70 ± 12	13 ± 10*

*P<0.05 vs preoperative measurement; EDV = end-diastolic volume, EF = ejection fraction

[Bach 1995, Bolling 1995, Bach 1996, Bolling 1998]. Importantly, all patients remain on maximal medical therapy; most have been able to tolerate a better regime with increased beta blockers and angiotensin-converting enzyme inhibitors. Mitral reconstruction by means of aggressive annuloplasty effectively corrects MR in patients with severe cardiomyopathy.

Further evidence exists to support the success of mitral valve repair in patients with cardiomyopathy. Akasaka et al. assessed coronary flow characteristics before and after mitral valve reconstruction in patients with MR and no coronary artery disease [Akasaka 1998]. Prior to reconstruction, coronary flow reserve was limited because of increased baseline coronary flow and flow velocity related to LV volume overload, hypertrophy and LV wall stress. The restriction improved following mitral valve reconstruction; reduction in baseline coronary flow and flow velocity occurred after LV preload, work and mass reduction [Akasaka 1998]. A restriction in the coronary flow reserve would seem probable in patients with MR and cardiomyopathy, and improved flow reserve and velocity would be expected following mitral valve repair. Ultimately, the mitral valve repair in this setting should lead to improvement in LV geometry.

Left Ventricular Remodeling

Patients with severe ventricular dilation from either ischemic or idiopathic cardiomyopathy have a very poor prognosis. Aside from transplantation, surgical interventions in patients with refractory heart failure have been generally contraindicated. Improved surgical therapies involving ventricular reconstruction to reduce wall stress and ventricular chamber dimensions are rapidly expanding and evolving.

Batista and coworkers developed an operation for patients with end-stage dilated cardiomyopathy of various etiologies [Batista 1996, Batista 1997]. The objective of the operation is to return the enlarged heart to a normal diameter, thereby reducing LV wall tension (via a mechanism related to the law of Laplace). To reduce heart diameter, large segments of LV wall are resected. The heart is then reconstructed to decrease LV diameter. Reported perioperative mortality is approximately 22%, and two-year mortality is approximately 45%. Most survivors have improved clinical condition [Batista 1997].

Of the 62 patients who underwent partial left ventriculectomy at the Cleveland Clinic Foundation between May 1996 and December 1998, 59 also had concomitant mitral valve repair. A complete description of study population, methodology and a report of early results has previously been presented [McCarthy 1997]. Although 30% of patients continue to do well, this surgery is associated with a high risk of both early and late failure, which remains largely unpredictable. It is thought that detrimental effects on diastolic compliance offset the presumed benefits of improved systolic function [Dickstein 1997]. McCarthy and colleagues at the Cleveland Clinic Foundation have abandoned this procedure as an alternative to cardiac transplantation.

A more promising operation is LV reconstruction for ischemic cardiomyopathy. Revascularization following an anterior MI may improve survival [Bertelsen 1997, Senior 1999], but the infarcted anterior wall and septum segment remain akinetic unless repaired surgically. Remote (noninfarcted) myocardia must compensate to ensure adequate cardiac output. Ultimately, heart failure ensues as LV geometry becomes spherical [Dor 1997a].

For many years, cardiac specialists have felt that patients with ventricular aneurysms show improvement in heart failure symptoms following ventricular aneurysmectomy [Cooley 1959]. The operative mortality and concerns over the ideal means of ventricular remodeling have prompted continuous interest in improving surgical approaches. Ventricular reconstruction, benefiting both dyskinetic ventricles and akinetic ventricles, has evolved from linear aneurysm repairs to more complicated repairs that exclude the infarcted septum and free wall [McCarthy 1999].

Infarct exclusion, the technique adopted at the Cleveland Clinic Foundation that evolved from the combined experience of Jatene, Dor, Cooley and David [Jatene 1985, Dor 1997b, Moreira 1998], excludes the akinetic areas of the LV apex and septum, resulting in a more elliptical shape and thus improved cardiac function (Figure 7, ◉). More than 100 Cleveland Clinic patients have undergone this infarct exclusion, which is frequently associated with coronary artery bypass (86%) and mitral valve surgery (44%). Low perioperative mortality (2%) and late failure rates (90%) have been demonstrated. As documented by three-dimensional echocardiography, decreased LV volumes and improved LVEFs have been observed.

Surgical therapies for heart failure are rapidly expanding and evolving. The concept of high mortality and morbidity of surgical interventions in patients with end-stage heart disease no longer applies because of improvements in preoperative selection, intraoperative techniques and postoperative care. Results are acceptable when operative techniques are combined with optimal medical management of heart failure, and many patients can avoid or postpone transplantation. This strategy will allow preservation of the limited number of donor organs for patients who have no other alternative.

Cardiopulmonary Bypass Weaning

The selection of an appropriate therapeutic regimen, especially in patients with preexisting cardiac dysfunction prior to surgery, is a crucial element for successful separation from cardiopulmonary bypass (CPB). No definitive studies exist to determine which treatment modality, or combination of treatments, is optimal in this patient population. This is further evidenced by the observation that the use of certain proven treatments such as milrinone administration varies from less than 10% to 80%. However, several trends and guidelines are evident. Prophylactic inotrope administration, used to assist separation from CPB, does not result in damage to the myocardium. When tachycardia is avoided and coronary perfusion pressure maintained, prophylactic inotropes might benefit patients with preexisting myocar-

dial dysfunction by facilitating a smooth and accelerated separation from CPB [Hardy 1993].

Down-regulation of beta-receptors during cardiac surgery has led to the development of agents that act independently of this system [Boldt 1993]. Phosphodiesterase inhibitors (PDEIs) have demonstrated remarkable effectiveness in facilitating weaning from CPB [Hamada 1999]; in fact, Columbia University and others such as the Cleveland Clinic Foundation [Boldt 1992, Butterworth 1993, Hardy 1993, Badner 1994, De Hert 1995, Orime 1998a, Orime 1998b] have come to refer to these agents as "balloon pumps in a bottle" [Orime 1999]. Prophylactic support of the circulation during separation from CPB, especially with PDEIs, may be indicated in this specific patient population as part of the strategy to ensure maximal preservation of myocardial function.

In addition to inotropic support regimens, appropriate early use of mechanical support can preserve end-organ function while allowing the heart precious time for recovery. Especially after an acute MI, repletion of ATP stores can take three days and will occur more quickly in a well-supported patient with a decompressed LV. Although a benefit of IABPs is their ease of insertion, the net additional power supplied to the left-sided circulation is only about 10%. At Columbia University, the criteria for institution of more aggressive support includes hemodynamic requirements: low cardiac output, elevated pulmonary arterial pressures (PAPs), elevated central venous pressures (CVPs) and tachycardia with arrhythmias. In addition, continual monitoring of physiologic criteria (e.g., mixed venous oxygen saturation, urine output) is employed. Use of LV support systems in this setting might be warranted and should be instituted early enough to prevent irreversible end-organ injury.

Transesophageal Echocardiography and High-Risk Cardiac Surgery

Patient Case. The patient was transferred to the operating room for a cardiac transplant after three weeks of biventricular assist with the Thoratec device (see Movie). During the device insertion period, the patient had experienced repeated episodes of bleeding with intermittent drops in the ventricular assist device (VAD) flow. Although the patient was hemodynamically stable at the time of transplantation, echocardiography demonstrated several well-defined, loculated collections of fluid around the heart that were confirmed at explantation to be pericardial effusions.

Transesophageal echocardiography (TEE) has become an indispensable monitoring tool in high-risk cardiac surgical procedures [Shanewise 1999]. Early recognition of the utility of intraoperative TEE focused on the assessment of the adequacy of mitral valve repair [Freeman 1992]. Today, its role has expanded to include the diagnosis of hemodynamic disorders and assessment of both anatomical and functional abnormalities as well as monitoring the rapid changes in cardiac function that occur during cardiac surgical procedures [Swenson 1996, Poelaert 1998, Garduno 1999, Lambert 1999, Swenson 1999, Willens 1999, Willens 2000].

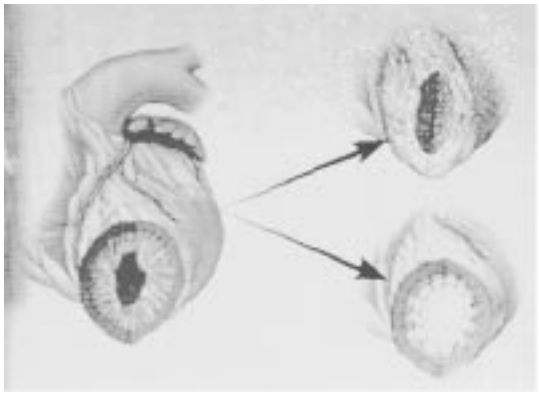

Figure 7. Infarct exclusion of the akinetic areas of the left ventricular apex and septum.

Clinical studies have examined the role of TEE and its indications in intraoperative decision-making. In patients with acute or chronic hemodynamic disturbances or patients at risk for myocardial ischemia who were monitored with two-lead electrocardiography, radial and pulmonary artery catheters and biplane or multiplane TEE, the most important guiding factor in 25% of surgical interventions was TEE. Further, TEE was the most important monitor in guiding anti-ischemic therapy, fluid administration, vasopressor or inotrope administration, vasodilator therapy and depth of anesthesia [Kolev 1998]. In addition, Bergquist et al. have reported that TEE is often influential in guiding decision-making during elective myocardial revascularization procedures [Bergquist 1996]. To guide clinical decisions, the American Society of Echocardiography (ASE) and Society of Cardiovascular Anesthesiologists (SCA) have established guidelines for performing comprehensive intraoperative TEE examinations [Shanewise 1999].

The numerous pitfalls that can accompany the sophisticated TEE technology are associated with the physics of ultrasound, presence of artifacts and the ability to alter images with changes in console settings. Practical limitations include operator dependence and the imperfect relationship between echocardiography findings and physiological reality. For example, the amount of mitral insufficiency observed in an anesthetized patient may not reflect the competence of the valve during activities of normal living. In the following review of the limits of intraoperative echocardiography, EF will serve as an illustrative example.

The most common systolic function index determined from echocardiography is EF. Typically, EF is derived from the change in the area of the short-axis slice of the LV at the midpapillary level. Since TEE provides two-dimensional images, it is assumed that area is linearly related to volume and an area change would be identical to a volume change. This assumption may be invalid, however, secondary to the heterogeneity of the chamber. For example, a dilated, akinetic apex would not impact the above-described EF calculation. More broadly stated, the estimation of EF is less robust in the presence of regional wall

motion abnormalities. Another practical limitation stems from the fact that the change in chamber area is not typically measured, which requires laborious planimetry or problematic automated edge detection, but rather is derived from a visual gestált that is obviously prone to observer error.

EF was established as a parameter to track systolic function deterioration in patients with heart disease. However, in the perioperative period, profound changes occur in the conditions under which the heart ejects. These conditions may result in EF changes that are unrelated to systolic function. One obvious example is the seemingly poor contractile function of the LV while on partial CPB. Two important alterations in loading conditions include reduced preload due to the diversion of venous return to the bypass pump and increased afterload due to maintenance of aortic pressure with the bypass pump. Clearly, assessment of systolic function is impossible under these extremely altered loading conditions. One less obvious example of the limitations associated with EF was noted during partial left ventriculectomy (Batista procedure): increased EF was accomplished by a reduction in EDV; the perceived benefits to heart function were not realized.

Acute Cardiovascular Collapse After Cardiac Surgery

A high index of suspicion is important when evaluating a patient with unexplained acute cardiovascular dysfunction following cardiac surgery. A variety of clinical problems can produce cardiovascular collapse, and multiple mechanisms may be responsible. Diagnosis and treatment are important when acute decompensation occurs. A differential diagnosis of acute-onset hypotension includes evaluation of the cardiac, inflammatory, neoplastic, degenerative, toxic, congenital, autoimmune, traumatic and endocrine pathophysiological processes [Hravnak 1997]. Because blood pressure (BP) is the product of cardiac output and total peripheral resistance, hypotension results from an abnormality in one or both of these parameters. Artifactual BP changes should be evaluated before instituting immediate therapy.

Administration of Sedative, Hypnotic or Anesthetic Drugs

Precipitous hypotension often follows administration of intravenous sedative, hypnotic or anesthetic drugs in critically ill patients [Levy 1992, Wahr 1996]. The effect typically occurs in patients who are hypovolemic or require a high sympathetic tone to maintain perfusion pressure [Shafer 1998]. Sedating these patients with one agent or a combination (e.g., benzodiazepines or opioids) causes their basal catecholamine levels to fall and BP to decrease.

Anaphylaxis/Bronchospasm

Any medication or blood product administered in the perioperative setting can be associated with unintended consequences or side effects. Patients are exposed to occult antigens, including latex, drug additives and drug preservatives, and serious adverse drug reactions may occur. As a result, clinicians must be prepared to treat anaphylaxis, the most life-threatening form of adverse reaction [Levy 1992]. When acute hypotension ensues following blood administration, anaphylaxis should always be considered as a cause [Levy 1992]. Bronchospasm and wheezing can also exacerbate right ventricular dysfunction. Furthermore, transfusion-related acute lung injury, an immunological reaction, presents similarly to anaphylaxis.

Disconnection or Overdosage of Vasoactive Infusions

Inadvertent discontinuation of vasoconstrictor infusions in critically ill patients must be considered a cause of precipitous hypotension. Catecholamines should be infused into central venous catheters whenever possible to avoid this problem. In addition, inadvertent overdosage when sodium nitroprusside or nitroglycerin is administered intravenously can occur after accidental flushing. Infusion rates, administration sites and patency of intravenous cannulas should be reevaluated after precipitous hypotension in patients receiving vasoactive medications.

Dysrhythmias

Bradycardia, rapid ventricular rates or sudden loss of sinus rhythm in patients with valvular heart disease (e.g., mitral or aortic stenosis) may seriously compromise LV filling and decrease cardiac output to produce shock. Heart rate and rhythm should be evaluated in all patients who develop acute cardiovascular dysfunction. Amiodarone administration has produced life-saving results in patients with recurrent ventricular tachycardia or ventricular fibrillation [Levy 1992, Kowey 1995].

Myocardial Ischemia

Following protamine reversal of anticoagulation, patients are acutely hypercoagulable, and graft closure, especially when target vessels were problematic, is always important to consider. Incomplete revascularization of a patient or even coronary or internal mammary artery spasm may compromise myocardial blood flow. In addition, open chamber procedures carry the risk of coronary air emboli, which can manifest as acute myocardial ischemia after resumption of LV output. TEE is extremely useful in assessing the adequacy of de-airing maneuvers.

Tamponade

Cardiac tamponade may occur and is often associated with excessive chest tube drainage that suddenly decreases following chest closure [Chuttani 1994]. If the heart is edematous and the chest cavity is small, chest closure can also cause acute hemodynamic compromise in a critically ill patient.

Pneumothorax/Hemothorax

An unrecognized pneumothorax or hemothorax may appear as precipitous hypotension with or without wheezing during mechanical ventilation in the operating room or intensive care unit; it may be confused with anaphylaxis. Chest auscultation and clinical suspicion are important for diagnosing this reversible problem. Signs of tension pneumothorax include acute hypotension, hypoxemia and hyperresonance to percussion, decreased breath

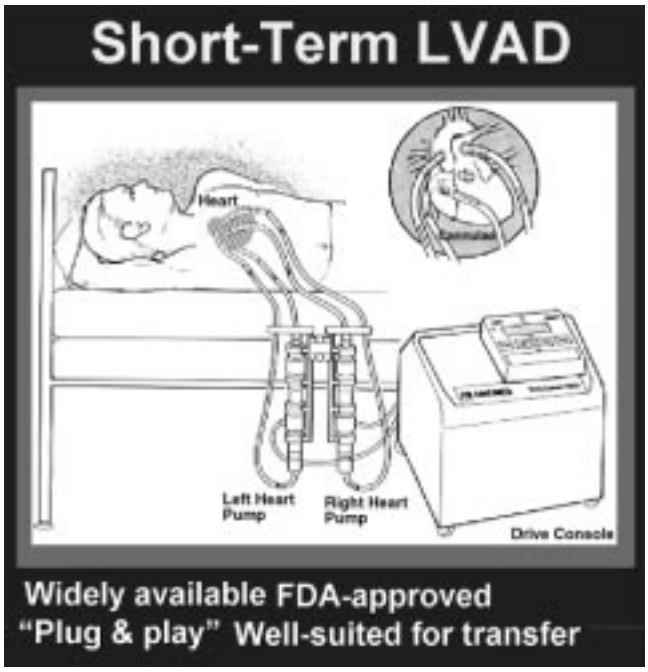

Figure 8. Abiomed LVAD.

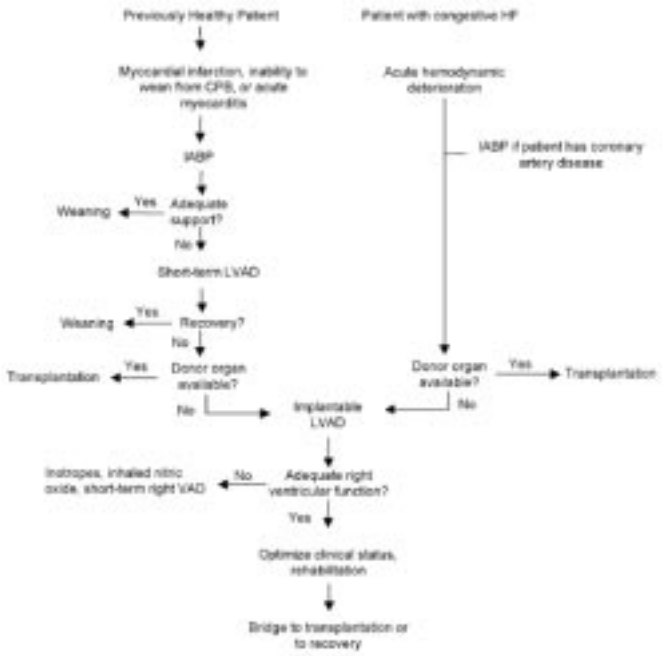

Figure 9. Scheme for selection of patients with acute cardiac disease or congestive heart failure for implantation of LVADs. (Adapted with permission from Goldstein DJ et al. [Goldstein 1998]).

sounds on the affected side and increased peak inspiratory pressure [Barton 1999]. Time should not be wasted obtaining a portable chest radiograph if life-threatening hypotension is present. Air should be immediately aspirated with a 14-gauge intravenous catheter placed in the second intercostal space over the midclavicular line on the affected side or with chest tube insertion.

Progressive Biventricular Dysfunction

Patients with preexisting heart failure or patients without adequate myocardial preservation may develop reperfusion injury and, thus, progressive ventricular dysfunction. In addition to beta-adrenergic down regulation, stress responses from surgery and extracorporeal circulation may further exacerbate ventricular dysfunction [Levy 1993].

Complications of Inotropic Support

Despite major advances in inotropic medications and the understanding of their proper use, approximately 6% of patients require more aggressive therapy. Failure of inotropic therapy can be heralded by end-organ dysfunction, including oliguria and coagulopathy, and can be predicted by poor mixed venous oxygen saturation. Solutions include earlier use of appropriate inotropic support, combined with adjunctive techniques to provide stability during the critical first 12 hours following CPB. For example, aggressive administration of a PDEI such as milrinone results in improved biventricular contractility and reduced right-sided circulatory failure in patients otherwise dying after cardiac surgery [Feneck 1991, George 1992, Sherry 1993, Kikura 1997]. However, despite improved hemodynamics, systemic hypotension, which can be disconcerting, periodically occurs with PDEIs. In patients with vasodilatory shock, use of arginine vasopressin (AVP) at physiologic rather than pharmacologic doses (0.1 units/min.) has demonstrated reliable increases in systemic BP without causing end-organ ischemia [Argenziano 1997]. Patients with neurohormonal heart failure changes are often resistant to alpha-agonist medications as monotherapy and require restoration of depleted AVP to regain appropriate response to sympathetic agents. In the reparative surgery population at Columbia University, a 10% incidence of vasodilatory shock, defined as a mean arterial pressure below 65 mm Hg despite a cardiac index above 2.4L/min./m^2, has been identified [Argenziano 1998]. Unlike patients with cardiogenic shock who have appropriately elevated AVP levels, vasodilatory shock patients have subphysiological circulating hormone concentrations.

Similarly, the inability to substantively improve the ventricular contractility and hemodynamics of critically ill cardiac patients mandates mechanical support in suitable candidates. Traditionally at Columbia University, IABP support is initiated if patients remain tachycardic with elevated right-sided pressures despite combined use of milrinone and norepinephrine with additional vasopressin as indicated. However, in the absence of ongoing myocardial ischemia, IABP support only increases net left-sided power output by 10%. In profound ventricular failure, early institution of a VAD (Figure 8, ◎) will support end-organ perfusion while allowing the ischemic myocardium the required two-to-three days to regenerate depleted energy

stores. If, after this short period, attempts to reduce VAD flows after reinstitution of inotropic medications prove unsuccessful, insertion of longer-term implantable VADs is considered (Figure 9, ◉) [Goldstein 1998]. This approach has resulted in hospital discharge rates in excess of 70% rather than the historical standard of 25%.

Patient Case. A 69-year-old woman with a history of coronary artery disease presented with MR (4^+), EF 20% and an apical aneurysm. Preoperatively, patient hemodynamic measurements included BP 110/60 mm Hg, pulmonary artery pressure (PAP) 50/24 mm Hg and central venous pressure (CVP) 9 mm Hg without inotropic support. The patient underwent Dor aneurysmectomy, bowtie mitral valve repair, and coronary artery bypass grafting. Postoperatively, the patient was administered intravenous dobutamine; hemodynamics on dobutamine were BP 75/40 mm Hg; PAP 40/20 mm Hg and CVP 16 mm Hg. The patient experienced increasing tachycardia on dobutamine, and CPB weaning was difficult. Intravenous milrinone was started. The patient's LV function and hemodynamics improved (BP 120/60 mm Hg; PAP 28/12 mm Hg; CVP 11 mm Hg), and the patient was successfully separated from CPB.

CONCLUSION

Management of the high-risk cardiac surgical patient requires the best of modern medicine, namely, sophisticated technology and a team of concerned medical and nursing specialists. Several options are now available for physicians to treat the ever-increasing number of heart failure patients. Surgical techniques, including mitral valve repair with an undersized flexible annuloplasty ring, and infarct exclusion, have shown promising results. Similarly, advances in monitoring techniques, including TEE, and medical therapy with aggressive inotropic support, provide the practitioner with options to improve patient outcome.

REFERENCES

1. Adams KF, Jr., Zannad F. Clinical definition and epidemiology of advanced heart failure. Am Heart J 135(6 pt 2):S204–15, 1998.
2. Akasaka T, Yoshida K, Hozumi T, et al. Restricted coronary flow reserve in patients with mitral regurgitation improves after mitral reconstructive surgery. J Am Coll Cardiol 32(7): 1923–30, 1998.
3. Akins CW, Hilgenberg AD, Buckley MJ, et al. Mitral valve reconstruction versus replacement for degenerative or ischemic mitral regurgitation. Ann Thorac Surg 58(3):668–75, 1994.
4. Alvarez JM, Deal CW, Loveridge K, et al. Repairing the degenerative mitral valve: ten- to fifteen-year follow-up. J Thorac Cardiovasc Surg 112(2):238–47, 1996.
5. American Heart Association. 2000 Heart and Stroke Statistical Update. Dallas, Tex: American Heart Association, 1999.
6. Anguita M, Arizon JM, Bueno G, et al. Clinical and hemodynamic predictors of survival in patients aged <65 years with severe congestive heart failure secondary to ischemic or nonischemic dilated cardiomyopathy. Am J Cardiol 72(5):413–7, 1993.
7. Argenziano M, Chen JM, Choudhri AF, et al. Management of vasodilatory shock after cardiac surgery: identification of predisposing factors and use of a novel pressor agent. J Thorac Cardiovasc Surg 116(6):973–80, 1998.
8. Argenziano M, Choudhri AF, Oz MC, et al. A prospective randomized trial of arginine vasopressin in the treatment of vasodilatory shock after left ventricular assist device placement. Circulation 96(9 suppl):II286–90, 1997.
9. Bach DS, Bolling SF. Early improvement in congestive heart failure after correction of secondary mitral regurgitation in end-stage cardiomyopathy. Am Heart J 129(6):1165–70, 1995.
10. Bach DS, Bolling SF. Improvement following correction of secondary mitral regurgitation in end-stage cardiomyopathy with mitral annuloplasty. Am J Cardiol 78(8):966–9, 1996.
11. Badner NH, Murkin JM, Shannon NA. An amrinone bolus prior to weaning from cardiopulmonary bypass improves cardiac function in mitral valve surgery patients. J Cardiothorac Vasc Anesth 8(4):410–4, 1994.
12. Barton ED. Tension pneumothorax. Curr Opin Pulm Med 5(4):269–74, 1999.
13. Batista RJV, Santos JLV, Takeshita N, et al. Partial left ventriculectomy to improve left ventricular function in end-stage heart disease [published erratum appears in J Card Surg 1997 Jan–Feb;12(1):ix]. J Card Surg 11(2):96–7, 1996.
14. Batista RJV, Verde J, Nery P, et al. Partial left ventriculectomy to treat end-stage heart disease. Ann Thorac Surg 64(3): 634–8, 1997.
15. Beck JR, Mongero LB, Kroslowitz RM, et al. Inhaled nitric oxide improves hemodynamics in patients with acute pulmonary hypertension after high-risk cardiac surgery. Perfusion 14(1):37–42, 1999.
16. Bergquist BD, Bellows WH, Leung JM. Transesophageal echocardiography in myocardial revascularization: II. Influence on intraoperative decision making. Anesth Analg 82(6): 1139–45, 1996.
17. Bertelsen CA, Kjøller M, Høier-Madsen K, et al. Influence of complete revascularization on long-term survival after coronary artery bypass surgery. Scand Cardiovasc J 31(5):271–4, 1997.
18. Boldt J, Hammermann H, Hempelmann G. What is the place of the phosphodiesterase inhibitors? Eur J Anaesthesiol 10(suppl 8):33–7, 1993.
19. Boldt J, Knothe C, Zickmann B, et al. The role of enoximone in cardiac surgery. Br J Anaesth 69(1):45–50, 1992.
20. Bolling SF, Deeb GM, Brunsting LA, et al. Early outcome of mitral valve reconstruction in patients with end-stage cardiomyopathy. J Thorac Cardiovasc Surg 109(4):676–82, 1995.
21. Bolling SF, Pagani FD, Deeb GM, et al. Intermediate-term outcome of mitral reconstruction in cardiomyopathy. J Thorac Cardiovasc Surg 115(2):381–8, 1998.
22. Butterworth JF, Royster RL, Prielipp RC, et al. Amrinone in cardiac surgical patients with left-ventricular dysfunction. A prospective, randomized placebo-controlled trial. Chest 104(6):1660–7, 1993.
23. Christenson JT, Simonet F, Schmuziger M. The effect of pre-

operative intra-aortic balloon pump support in high risk patients requiring myocardial revascularization. J Cardiovasc Surg (Torino) 38(4):397–402, 1997.
24. Chuttani K, Tischler MD, Pandian NG, et al. Diagnosis of cardiac tamponade after cardiac surgery: relative value of clinical, echocardiographic, and hemodynamic signs. Am Heart J 127(4 Pt 1):913–8, 1994.
25. Colucci W, Braunwald E. Pathophysiology of heart failure. In Braunwald E (ed.), Heart Disease, A textbook of cardiovascular medicine. Philadelphia: W.B. Saunders Co., 394–420, 1997.
26. Cooley DA, Henly WS, Amad KH, et al. Ventricular aneurysm following myocardial infarction: results of surgical treatment. Ann Surg 150:595–610, 1959.
27. Dalrymple-Hay MJ, Alzetani A, Aboel-Nazar S, et al. Cardiac surgery in the elderly. Eur J Cardiothorac Surg 15(1):61–6, 1999.
28. David TE, Uden DE, Strauss HD. The importance of the mitral apparatus in left ventricular function after correction of mitral regurgitation. Circulation 68(3 pt 2):II-76–82, 1983.
29. De Hert SG, Moens MM, Jorens PG, et al. Comparison of two different loading doses of milrinone for weaning from cardiopulmonary bypass. J Cardiothorac Vasc Anesth 9(3): 264–71, 1995.
30. Dickstein ML, Spotnitz HM, Rose EA, et al. Heart reduction surgery: an analysis of the impact on cardiac function. J Thorac Cardiovasc Surg 113(6):1032–40, 1997.
31. Dor V. Left ventricular aneurysms: the endoventricular circular patch plasty. Semin Thorac Cardiovasc Surg 9(2):123–30, 1997b.
32. Dor V, Di Donato M. Ventricular remodeling in coronary artery disease. Curr Opin Cardiol 12(6):533–7, 1997a.
33. Dzau VJ. Renal and circulatory mechanisms in congestive heart failure. Kidney Int 31(6):1402–15, 1987.
34. Feneck RO. Effects of variable dose milrinone in patients with low cardiac output after cardiac surgery. European Multicenter Trial Group. Am Heart J 121(6 pt 2):1995–9, 1991.
35. Ferraris VA, Ferraris SP, Singh A. Operative outcome and hospital cost. J Thorac Cardiovasc Surg 115(3):593–602, 1998.
36. Francis GS, Benedict C, Johnstone DE, et al. Comparison of neuroendocrine activation in patients with left ventricular dysfunction with and without congestive heart failure. A substudy of the Studies of Left Ventricular Dysfunction (SOLVD). Circulation 82(5):1724–9, 1990.
37. Francis GS, Goldsmith SR, Levine TB, et al. The neurohumoral axis in congestive heart failure. Ann Intern Med 101(3):370–7, 1984.
38. Freeman WK, Schaff HV, Khandheria BK, et al. Intraoperative evaluation of mitral valve regurgitation and repair by transesophageal echocardiography: incidence and significance of systolic anterior motion. J Am Coll Cardiol 20(3):599–609, 1992.
39. Gaasch WH. Diagnosis and treatment of heart failure based on left ventricular systolic or diastolic dysfunction. JAMA 271(16):1276–80, 1994.
40. Gallino A, Jenni R, Hurni R, et al. Early results after mitral valvuloplasty for pure mitral regurgitation. Eur Heart J 8(8): 902–5, 1987.
41. Garduno C, Chew S, Forbess J, et al. Persistent left superior vena cava and partial anomalous pulmonary venous connection: incidental diagnosis by transesophageal echocardiography during coronary artery bypass surgery. J Am Soc Echocardiogr 12(8):682–5, 1999.
42. George M, Lehot JJ, Estanove S. Haemodynamic and biological effects of intravenous milrinone in patients with a low cardiac output syndrome following cardiac surgery: multicentre study. Eur J Anaesthesiol suppl 5:31–4, 1992.
43. Gheorghiade M, Cody RJ, Francis GS, et al. Current medical therapy for advanced heart failure. Am Heart J 135(6 pt 2): S231–48, 1998.
44. Goldman ME, Mora F, Guarino T, et al. Mitral valvuloplasty is superior to valve replacement for preservation of left ventricular function: an intraoperative two-dimensional echocardiographic study. J Am Coll Cardiol 10(3):568–75, 1987.
45. Goldstein DJ, Oz MC, Rose EA. Implantable left ventricular assist devices. N Engl J Med 339(21):1522–33, 1998.
46. Hamada Y, Kawachi K, Yamamoto T, et al. Effects of single administration of a phosphodiesterase III inhibitor during cardiopulmonary bypass: comparison of milrinone and amrinone. Jpn Circ J 63(8):605–9, 1999.
47. Hardy JF, Belisle S. Inotropic support of the heart that fails to successfully wean from cardiopulmonary bypass: the Montreal Heart Institute experience. J Cardiothorac Vasc Anesth 7(4 suppl 2):33–9, 1993.
48. Ho KK, Pinsky JL, Kannel WB, et al. The epidemiology of heart failure: the Framingham Study. J Am Coll Cardiol 22(4 suppl A):6A–13A, 1993.
49. Hravnak M, Boujoukos A. Hypotension. AACN Clinical Issues 8(3):303–18, 1997.
50. Hunt SA. Current status of cardiac transplantation. JAMA 280(19):1692–8, 1998.
51. Jatene AD. Left ventricular aneurysmectomy. Resection or reconstruction? J Thorac Cardiovasc Surg 89(3):321–31, 1985.
52. Katz AM. Cardiomyopathy of overload: a major determinant of prognosis in congestive heart failure. N Engl J Med 322(2):100–10, 1990.
53. Katz AM. Cardiomyopathy of overload: an unnatural growth response in the hypertrophied heart. Ann Intern Med 121(5):363–71, 1994.
54. Kikura M, Levy JH, Michelsen LG, et al. The effect of milrinone on hemodynamics and left ventricular function after emergence from cardiopulmonary bypass. Anesth Analg 85(1):16–22, 1997.
55. Kolev N, Brase R, Swanevelder J, et al. The influence of transoesophageal echocardiography on intra-operative decision making. A European multicentre study. European Perioperative TOE Research Group. Anaesthesia 53(8):767–73, 1998.
56. Kono T, Sabbah HN, Rosman H, et al. Left ventricular shape is the primary determinant of functional mitral regurgitation in heart failure. J Am Coll Cardiol 20(7):1594–8, 1992.
57. Kowey PR, Levine JH, Herre JM, et al. Randomized, double-blind comparison of intravenous amiodarone and bretylium in the treatment of patients with recurrent, hemodynamically destabilizing ventricular tachycardia or fibrillation. Circulation 92(11):3255–63, 1995.
58. Körfer R, El-Banayosy A, Arusoglu L, et al. Temporary pulsatile ventricular assist devices and biventricular assist

devices. Ann Thorac Surg 68(2):678–83, 1999.
59. Kuhn C, Muller-Werdan U, Schmitt DV, et al. Improved outcome of APACHE II score-defined escalating systemic inflammatory response syndrome in patients post cardiac surgery in 1996 compared to 1988-1990: the ESSICS-study pilot project. Eur J Cardiothorac Surg 17(1):30–7, 2000.
60. Lambert AS, Miller JP, Merrick SH, et al. Improved evaluation of the location and mechanism of mitral valve regurgitation with a systematic transesophageal echocardiography examination. Anesth Analg 88(6):1205–12, 1999.
61. Lenfant C. Report of the task force on research in heart failure. Circulation 90(3):1118–23, 1994.
62. Levit KR, Lazenby HC, Cowan CA, et al. National health expenditures, 1990. Health Care Financing Review 13(1): 29–54, 1991.
63. Levy JH. Anaphylactic reactions in anesthesia and intensive care. Boston: Butterworth-Heinemann Medical, 1992.
64. Levy JH. Support of the perioperative failing heart with preexisting ventricular dysfunction: currently available options. J Cardiothorac Vasc Anesth 7(4 suppl 2):46–51, 1993.
65. Little WC, Braunwald E. Assessment of cardiac function. In Braunwald E (ed.), Heart Disease, A textbook of cardiovascular medicine. Philadelphia: W.B. Saunders, 421–43, 1997.
66. McCarthy PM. New surgical options for the failing heart. J Heart Valve Dis 8(5):472–5, 1999.
67. McCarthy PM, Smedira NO, Vargo RL, et al. One hundred patients with the HeartMate left ventricular assist device: evolving concepts and technology. J Thorac Cardiovasc Surg 115(4):904–12, 1998.
68. McCarthy PM, Starling RC, Wong J, et al. Early results with partial left ventriculectomy. J Thorac Cardiovasc Surg 114(5):755–65, 1997.
69. Moreira LFP, Stolf NAG, Bocchi EA, et al. Partial left ventriculectomy with mitral valve preservation in the treatment of patients with dilated cardiomyopathy. J Thorac Cardiovasc Surg 115(4):800–7, 1998.
70. Nashef SAM, Roques F, Michel P, et al. European system for cardiac operative risk evaluation (EuroSCORE). Eur J Cardiothorac Surg 16(1):9–13, 1999.
71. Ninomiya J, Yamauchi H, Hosaka H, et al. Continuous transoesophageal echocardiography monitoring during weaning from cardiopulmonary bypass in children. Cardiovasc Surg 5(1):129–33, 1997.
72. O'Connell JB, Bristow MR. Economic impact of heart failure in the United States: time for a different approach. J Heart Lung Transplant 13(4):S107–12, 1994.
73. Opie LH. Mechanisms of cardiac contraction and relaxation. In Braunwald E (ed.), Heart Disease, A textbook of cardiovascular medicine. Philadelphia: W.B. Saunders, 360–93, 1997.
74. Orime Y, Shiono M, Hata H, et al. Effects of concomitant usage of milrinone and catecholamine for weaning from cardiopulmonary bypass. Jpn J Thorac Cardiovasc Surg 46(9): 803–9, 1998b.
75. Orime Y, Shiono M, Hata H, et al. Post-operative effects of olprinone after coronary artery bypass grafting. Ann Thorac Cardiovasc Surg 4(6):340–6, 1998a.
76. Orime Y, Shiono M, Hata H, et al. Effects of phosphodiesterase inhibitors after coronary artery bypass grafting. Jpn Circ J 63(2):117–22, 1999.
77. Phillips HR, Levine FH, Carter JE, et al. Mitral valve replacement for isolated mitral regurgitation: analysis of clinical course and late postoperative left ventricular ejection fraction. Am J Cardiol 48(4):647–54, 1981.
78. Pinson CW, Cobanoglu A, Metzdorff MT, et al. Late surgical results for ischemic mitral regurgitation. Role of wall motion score and severity of regurgitation. J Thorac Cardiovasc Surg 88(5 Pt 1):663–72, 1984.
79. Pitarys CJ, Forman MB, Panayiotou H, et al. Long-term effects of excision of the mitral apparatus on global and regional ventricular function in humans. J Am Coll Cardiol 15(3):557–63, 1990.
80. Poelaert J, Schmidt C, Colardyn F. Transoesophageal echocardiography in the critically ill. Anaesthesia 53(1):55–68, 1998.
81. Poldermans D, Boersma E, Bax JJ, et al. The effect of bisoprolol on perioperative mortality and myocardial infarction in high-risk patients undergoing vascular surgery. N Engl J Med 341(24):1789–94, 1999.
82. Rankin JS, Feneley MP, Hickey MS, et al. A clinical comparison of mitral valve repair versus valve replacement in ischemic mitral regurgitation. J Thorac Cardiovasc Surg 95(2):165–77, 1988.
83. Rich MW. Heart failure. Cardiol Clin 17(1):123–35, 1999.
84. Sarris GE, Cahill PD, Hansen DE, et al. Restoration of left ventricular systolic performance after reattachment of the mitral chordae tendineae. The importance of valvular-ventricular interaction. J Thorac Cardiovasc Surg 95(6):969–79, 1988.
85. Savage RM, Cosgrove DM. Systematic transesophageal echocardiographic examination in mitral valve repair: the evolution of a discipline into the twenty-first century [editorial]. Anesth Analg 88(6):1197–9, 1999.
86. Savage RM, Lytle BW, Aronson S, et al. Intraoperative echocardiography is indicated in high-risk coronary artery bypass grafting. Ann Thorac Surg 64(2):368–73, 1997.
87. Schrier RW, Abraham WT. Hormones and hemodynamics in heart failure. N Engl J Med 341(8):577–85, 1999.
88. Senior R, Kaul S, Lahiri A. Myocardial viability on echocardiography predicts long-term survival after revascularization in patients with ischemic congestive heart failure. J Am Coll Cardiol 33(7):1848–54, 1999.
89. Shafer A. Complications of sedation with midazolam in the intensive care unit and a comparison with other sedative regimens. Crit Care Med 26(5):947–56, 1998.
90. Shanewise JS, Cheung AT, Aronson S, et al. ASE/SCA guidelines for performing a comprehensive intraoperative multiplane transesophageal echocardiography examination: recommendations of the American Society of Echocardiography Council for Intraoperative Echocardiography and the Society of Cardiovascular Anesthesiologists Task Force for Certification in Perioperative Transesophageal Echocardiography. J Am Soc Echocardiogr 12(10):884–900, 1999.
91. Sherry KM, Locke TJ. Use of milrinone in cardiac surgical patients. Cardiovasc Drugs Ther 7(4):671–5, 1993.
92. Smedira NG, Wudel JH, Hlozek CC, et al. Venovenous extracorporeal life support for patients after cardiotomy. ASAIO J 43(5):M444–6, 1997.
93. Stevenson LW, Fowler MB, Schroeder JS, et al. Poor survival of patients with idiopathic cardiomyopathy considered too

well for transplantation. Am J Med 83(5):871–6, 1987.
94. Swenson JD, Bull DA. Intraoperative diagnosis and treatment of pleural effusion based on transesophageal echocardiographic findings. Anesth Analg 89(2):309–10, 1999.
95. Swenson JD, Harkin C, Pace NL, et al. Transesophageal echocardiography: an objective tool in defining maximum ventricular response to intravenous fluid therapy. Anesth Analg 83(6):1149–53, 1996.
96. Tischler MD, Cooper KA, Rowen M, et al. Mitral valve replacement versus mitral valve repair. A Doppler and quantitative stress echocardiographic study. Circulation 89(1): 132–7, 1994.
97. Wahr JA, Plunkett JJ, Ramsay JG, et al. Cardiovascular responses during sedation after coronary revascularization. Incidence of myocardial ischemia and hemodynamic episodes with propofol versus midazolam. The Institutions of the McSPI Research Group. Anesthesiology 84(6):1350–60, 1996.
98. Warner CD, Weintraub WS, Craver JM, et al. Effect of cardiac surgery patient characteristics on patient outcomes from 1981 through 1995. Circulation 96(5):1575–9, 1997.
99. Willens HJ, Kessler KM. Transesophageal echocardiography in the diagnosis of diseases of the thoracic aorta: part I—aortic dissection, aortic intramural hematoma, and penetrating atherosclerotic ulcer of the aorta. Chest 116(6):1772–9, 1999.
100. Willens HJ, Kessler KM. Transesophageal echocardiography in the diagnosis of diseases of the thoracic aorta: part II—atherosclerotic and traumatic diseases of the aorta. Chest 117(1):233–43, 2000.