JACC: CARDIOVASCULAR INTERVENTIONS
VOL. 1, NO. 5, 2008
© 2008 BY THE AMERICAN COLLEGE OF CARDIOLOGY FOUNDATION
ISSN 1936-8798/08/$34.00
PUBLISHED BY ELSEVIER INC.
DOI: 10.1016/j.jcin.2008.07.002

STATE-OF-THE-ART PAPER

Hybrid Cardiovascular Procedures

John G. Byrne, MD, FACC, Marzia Leacche, MD, Douglas E. Vaughan, MD, FACC, David X. Zhao, MD, FACC

Nashville, Tennessee

A hybrid strategy combines the treatments traditionally available only in the catheterization laboratory with those traditionally available only in the operating room to offer patients the best available therapies for any given set of cardiovascular lesions. Examples include hybrid coronary revascularization (coronary artery bypass grafting [CABG]/percutaneous coronary intervention [PCI]) wherein a left internal mammary artery graft is placed on the left anterior descending artery (left anterior descending coronary artery [LAD]) either by minimally invasive or open technique and combined with PCI of non-LAD vessels. Other examples include minimally invasive valve surgery combined with PCI to coronary lesions (valve/PCI), to convert a high-risk valve/CABG into a lower-risk isolated minimally invasive valve procedure. Several questions remain unresolved, such as the order in which surgery and PCI should be performed, the duration of the staging of the 2 procedures, antiplatelet strategies, the costs, and the logistics. Other areas in which hybrid approaches are being developed include hybrid endomyocardial/epicardial atrial fibrillation procedures and hybrid aortic arch debranching combined with endovascular grafting for thoracic aortic procedures. The key requirement in all of these approaches is the need for collaboration between cardiac surgeons, vascular surgeons, and interventional cardiologists to obtain optimal patient outcomes. (J Am Coll Cardiol Intv 2008;1:459–68) © 2008 by the American College of Cardiology Foundation

A hybrid strategy combines the treatments traditionally available only in the catheterization laboratory with those traditionally available only in the operating room, to offer patients the best available combination of treatments for any given set of cardiovascular lesions. The concept is not new (1,2). Cardiac surgeons and interventional cardiologists have been performing hybrid procedures since the first percutaneous intervention was followed later by a cardiac surgical procedure. When restenosis after percutaneous coronary intervention (PCI) was more frequent than the modern PCI results, hybrid procedures were common, only they were staged by days, weeks, or perhaps months. In the modern era, a hybrid procedure refers to the combination of traditional surgery and percutaneous intervention, staged by minutes, hours, or at most, days. This more compressed staging of hybrid procedures has regained interest as cardiac surgeons have improved techniques for minimally invasive surgical approaches, while interventional cardiologists have at their disposal improved devices and have developed skills that have enabled them to become more aggressive in their percutaneous interventions. Whereas interventional cardiologists are becoming "surgeons" with more invasive tools, surgeons are becoming "interventional cardiologists" with less invasive tools. Hence, the division between the 2 specialties has become blurred, and we are meeting in the middle. With the increased complexity of patients referred to the catheterization laboratory and to surgery, a team approach combining the best available tools of both specialties seems appealing to minimize the procedural risk. Examples of hybrid strategies include hybrid coronary artery bypass grafting (CABG)/PCI, hybrid valve/PCI, percutaneous valve therapy, hybrid endocardial and epicardial atrial fibrillation (AF) procedures, and aortic de-

From The Vanderbilt Heart and Vascular Institute, Nashville, Tennessee.

Manuscript received May 27, 2008; revised manuscript received July 8, 2008, accepted July 12, 2008.

JACC: CARDIOVASCULAR INTERVENTIONS, VOL. 1, NO. 5, 2008
OCTOBER 2008:459–68

branching procedures combined with endovascular grafting for the treatment of complex thoracic aortic dissections or aneurysmal disease.

Hybrid CABG/PCI

Hybrid CABG/PCI is broadly defined as the combination of traditional surgical methods with PCIs. Examples include everything from the common scenario PCI of a culprit coronary lesion during an acute coronary syndrome followed by conventional CABG during the same hospitalization, to elective minimally invasive left internal mammary artery (LIMA) to the left anterior descending artery (LAD) with PCI to non-LAD lesions. The latter strategy attempts to combine the best aspects of CABG (the LIMA–LAD graft) with the best aspects of PCI. In minimally invasive direct coronary artery bypass grafting (MIDCAB), the LIMA is harvested through a small left anterior thoracotomy incision or lower hemisternotomy. The LIMA–LAD bypass is crafted through this limited incision on the beating heart (Figs. 1A and 1B). In 1996, Angelini et al. (1), in a series of 6 patients, reported the first series of MIDCAB LIMA–LAD, combined with percutaneous transluminal coronary angioplasty/stent to non-LAD vessels.

Closed-chest CABG surgery is performed with robotic systems, which allows manipulation of tissues within thoracic ports through the use of fine instruments and peripheral institution of cardiopulmonary bypass. At a separate operating console, the surgeon controls the instruments, while the operation is viewed stereoscopically (3-dimensional view). In 1999, Loulmet et al. (2) introduced totally endoscopic coronary artery bypass grafting (TECAB) of the LIMA–LAD using peripheral access for cardiopulmonary bypass. Later in 2000, Farhat et al. (3) performed the first TECAB with LIMA-LAD, and PCI to the left circumflex system.

Abbreviations and Acronyms

AF = atrial fibrillation
BMS = bare-metal stent(s)
CABG = coronary artery bypass grafting
DES = drug-eluting stent(s)
LAD = left anterior descending coronary artery
LIMA = left internal mammary artery
MIDCAB = minimally invasive direct coronary artery bypass grafting
OPCAB = off-pump coronary artery bypass
PCI = percutaneous coronary intervention
SVG = saphenous vein graft
TECAB = totally endoscopic coronary artery bypass grafting
TLR = target lesion revascularization

Rationale, Indications, and Contraindications of Hybrid CABG/PCI

Several trials have compared the outcomes of CABG surgery versus PCI in multivessel disease (4). In a recent review of 23 randomized studies comparing PCI and CABG, survival at 10 years was similar even among the diabetic population; however, the rate of repeat revascularization rate was higher than CABG along with lower rate of relief from angina (5). Only 1 study included in the review used drug-eluting stents (DES), which were introduced in 2003. Therefore, the majority of studies comparing the outcomes of CABG and PCI were done using bare-metal stents (BMS). Conversely, in a recent analysis of a large registry from New York state, CABG provided survival advantage and lower rates of myocardial infarction and repeat revascularization even when compared with DES at 18-month follow-up (6). The LIMA–LAD graft has excellent patency rates, which correlates with increased event-free survival. Recent reports suggest a 5-year patency rate between 92% and 99% (7–9) and at 10 years between 95% and 98% (10,11). The LIMA-LAD graft may be responsible for the majority of the benefit of CABG surgery.

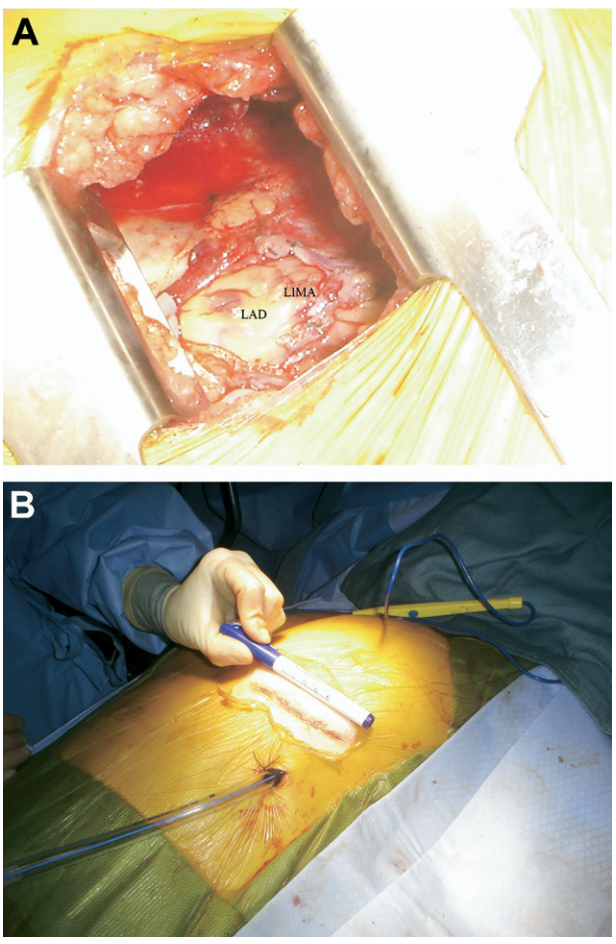

Figure 1. Minimally Invasive Direct Coronary Artery Bypass Grafting

(A) Minimally invasive direct coronary artery bypass grafting (MIDCAB) of the left internal mammary artery (LIMA) to left anterior descending coronary artery (LAD) through an anterior-lateral left thoracotomy on the beating heart. **(B)** Postoperative incision after MIDCAB.

Whether non-LAD vessels are treated with saphenous vein grafts (SVGs), PCI, or other modalities may be less important. This is the premise on which the modern era of hybrid coronary revascularization is based. Conversely, with PCI, the location of the lesion in the proximal LAD has been identified as an independent risk factor for in-stent restenosis with rates between 19% and 44% (12,13).

The second conduit used after the LIMA to bypass non-LAD vessels is the SVG, although the radial artery and right internal mammary artery are used as alternative conduits in selected patients. Failure rates for SVGs have been reported at 1 year between 1.6% and 30%, with an average of 20% (7,14,15). At 10 to 15 years of follow-up, 40% to 50% of the SVGs will have failed (11). These numbers may be compared with the rate of target lesion revascularization (TLR) in non-LAD vessels for stents. In the era of BMS, the TLR for proximal right/circumflex coronary artery stents has been reported to be 13.8% at 1 year (16). The SIRIUS (Sirolimus-eluting Stent Implantation) trial has reported a TLR rate at 2 years follow-up of 5.8%, compared with 21.3% in the control group (BMS) (17). These data are likely to improve in the near future with advances in DES technology that have narrowed the "reintervention gap" between surgery and PCI (18,19). Therefore, it is reasonable to hypothesize that PCI with DES is a better treatment to the non-LAD coronary artery disease than an SVG.

Indications for hybrid CABG/PCI (MIDCAB and TECAB) include patients with multivessel disease who have high-grade proximal disease of the LAD along with favorable lesions for PCI in the left circumflex and right coronary artery territories. Other areas where PCI may represent a superior alternative to SVG conduit include the lack or poor quality of the conduit, a nongraftable but stentable vessel (e.g., left circumflex lesions in the atrioventricular groove with small diffuse obtuse marginal), repeat operations in which PCI is preferable to avoid full cardiac dissection, or in patients with concomitant pre-existing organs dysfunction, or recent myocardial infarction, or severe atherosclerotic aortic disease.

Results of Hybrid CABG/PCI

Results for coronary hybrid revascularization are summarized in Table 1. Hybrid coronary revascularization is safe with low mortality rates (0% to 2%), low morbidity, and shorter intensive care unit and hospital stay. Other clear advantages are superior cosmetic results and faster recovery (1,3,20–38).

Despite these encouraging results, hybrid coronary revascularization is still reserved for few patients. To date, the largest series of patients from a single institution accounts for 70 patients enrolled over a 7-year period (31). This represents 5% of the center workload for CABG surgery. The reasons for the low recruitment include limitations of minimally invasive surgery and restenosis of BMS, but the largest factors have probably been logistical and political. We have performed 112 hybrid CABG/PCI procedures over about a 2-year period in our hybrid catheterization laboratory/operating room (Zhao DX, Leacche M, Balaguer JM, Boudoulas KD, Damp JA, Greelish JP, Byrne JG, unpublished data April 2005 to July 2007). There were no meaningful differences between risk-adjusted outcomes. Minimally invasive CABG surgery is limited by longer operating time, late wound complications, and more late pain because of rib retraction (39). Perhaps the greatest limitations, however, are the technical demands placed on the surgeon. Because MIDCAB and TECAB are technically demanding, anastomosis patency in the learning curve may be lower than conventional approaches. This is why we believe intraoperative imaging may eventually become mandatory for these procedures to become more commonplace. In our hybrid suite, all MIDCAB procedures undergo routine intraoperative completion angiography before chest closure (Fig. 2). The most experienced investigators report patency rates of the MIDCAB LIMA–LAD graft between 92% and 100% within 6 months of the procedure (23,30). Another limitation of hybrid coronary revascularization is stent restenosis and the need for repeat revascularization with BMS. In hybrid series, the stent restenosis at 6 months is 2.3% to 23% with an average across the literature of 11% (Table 1). The high rate seen in these series may be explained by the low use of DES. Moreover, in most of the earlier series of MIDCAB, percutaneous transluminal coronary angioplasty of the coronary vessels without stenting was the strategy adopted. In more recent series of MIDCAB, using only DES, Kon et al. (32) have reported at 1 year stent patency rates of 97%. In the RAVEL (A Randomized Comparison of a Sirolimus-Eluting Stent With a Standard Stent for Coronary Revascularization) trial (40), the DES have shown excellent survival free from TLR at 1, 3, and 5 years (99%, 93.8%, 89.7%), respectively. These exceptional results may not be reflected in the practice of most interventional cardiologists and surgeons because pattern of lesions may be more complex, such as bifurcated lesions, small vessels, or long lesions. Furthermore, over the last year, concern for higher incidence of late stent thrombosis compared with BMS has clouded the picture of DES (41,42). However, new data (43) from randomized trials and real-world registries have shown that DES are safe and efficacious.

2-Staged Hybrid Versus 1-Stop Hybrid CABG/PCI

All hybrid procedures are staged, the only distinction being the duration of the staging. For purposes of this discussion, 2-staged will be defined as PCI and CABG performed in 2 different operative suites, the 2 procedures separated by hours, days, or weeks, whereas 1-stop refers to hybrid

Table 1. Results of Hybrid Coronary Revascularization

Author (Ref. #)	Year	Patients (n)	Mortality (30-Day)	In-Hospital Morbidity (%)	LIMA Patency (Immediate) (%)	PTCA/Stent Restenosis (6 Months) (%)	Mean Follow-Up (Months)	Event-Free Survival (%)
MIDCAB + PTCA								
Lloyd et al. (20)	1999	18	0	11	100	6 (TLR)*	18	89
Isomura et al. (21)	2000	37	0	NA	100	NA	0–24	92
de Cannière et al. (22)	2001	20	0	15	100	5	24	95
Presbitero et al. (23)	2001	42	2	12	92	14 (TLR)†	18	83
Cisowski et al. (24)	2002	50	0	4	100	10	12	87
Stahl et al. (25)	2002	54	0	0	100	NA	12	87
MIDCAB + PTCA + PCI								
Angelini et al. (1)	1996	6	0	NA	NA	NA	NA	NA
Lewis et al. (26)	1999	14	0	21	100	0	1–44	93
Wittwer et al. (27)	2000	35	0	0	100	7	11	87
Riess et al. (28)	2002	57	0	7	98	24	24	NA
MIDCAB + PCI								
Zenati et al. (29)	1999	31	0	6	100	10	11	90
Us et al. (30)	2006	17	0	0	100	18	21	87
Gilard et al. (31)‡	2007	70	1.4	4.2	NA	2.3	33	97
Kon et al. (32)‡	2007	15	0	0	100	3	12	93
TECAB								
Lee et al. (33)	2004	6	0	0	NA	16	12	NA
Davidavicius et al. (34)	2005	20	0	0	100	0	19	100
Kiaii et al. (35)	2005	1	0	0	100	0	6	100
Katz et al. (36)§	2006	27	0	3.7	96 (3 months)	30 (BMS), 23.5 (DES)	3	70
Vassiliades et al. (37)‡	2006	47	0	0	99	6.6	7	90
Bonatti et al. (38)	2007	5	0	0	100	0	6	100

*Calculated on a per-patient basis. †TLR including revision or stenting of LIMA graft. ‡All DES used for PCI. §DES (63% of patients).

BMS = bare-metal stent; DES = drug-eluting stent; LIMA = left internal mammary artery; MIDCAB = minimally invasive direct coronary artery bypass grafting; NA = not applicable; PCI = percutaneous coronary intervention; PTCA = percutaneous transluminal coronary angioplasty; TECAB = totally endoscopic coronary artery bypass; TLR = target lesion revascularization.

CABG/PCI performed in a hybrid suite in 1 setting, staged by minutes. The appeal of the latter is multifold, including improved logistics, lower cost, and improved patient satisfaction.

In 2-staged hybrid procedures, performing PCI before CABG surgery allows aggressive multivessel stenting because if a complication arises or PCI is not successful, CABG can be performed later. The main disadvantages of this approach are performing PCI in an unprotected environment without the benefit of a LIMA–LAD graft, and later performing CABG under powerful antiplatelet agents, as well as no mid-term angiographic controls of the LIMA–LAD graft unless a third procedure is done—the completion angiogram before hospital discharge.

Performing PCI after CABG avoids antiplatelet-related bleeding complications during CABG, has the advantage of a protected environment with a LIMA–LAD graft, and the LIMA graft patency can be verified at the time of PCI. In the event of PCI complication/failure, however, a second, higher-risk operation needs to be performed. The latter should be rare, however, as emergent CABG after PCI has a low incidence (<1%) (44). For these reasons, most surgeons and cardiologists who practice 2-staged hybrid procedures have adopted the strategy of CABG first, followed a few days later by PCI.

Whether PCI is performed before or after CABG, in 2-staged hybrid procedures, 2 teams, 2 costs, longer hospital stays, logistical challenges, and potential risks related to handoffs must be considered, and many patients just do not want to undergo 2 procedures. For these reasons, we believe a 1-stop approach may be preferable.

When taking into account the limitations of 2-staged hybrid procedure, combining surgery and PCI in 1 procedure may be a superior approach because there is excellent monitoring, any complications can be resolved in 1 setting, and graft patency can be confirmed. Potential limitations include the use of antiplatelet agents, the unknown response of DES to heparin reversal with protamine, and the need to build an especially dedicated hybrid room with capabilities of both a complete operating room and a procedural suite (Fig. 3). Inconsistent data have been reported regarding the effect of clopidogrel in patients undergoing hybrid procedures. Some investigators have reported an increase in bleeding (45), whereas others have shown no differences

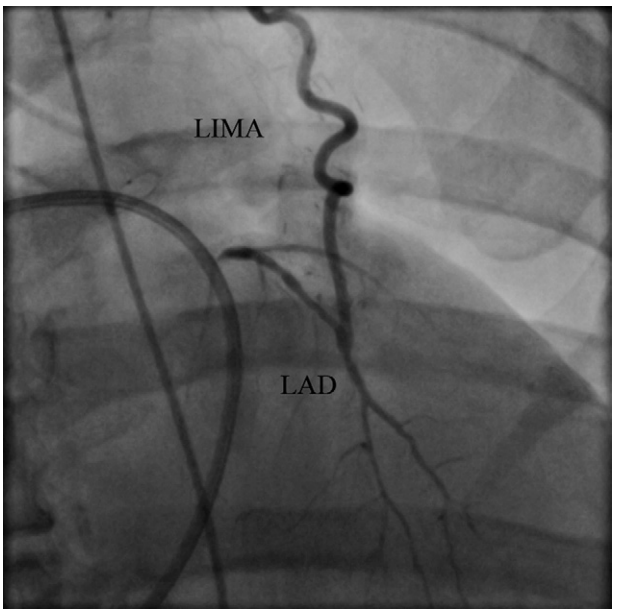

Figure 2. Completion Angiogram

A completion angiogram of a LIMA graft to the LAD after MIDCAB procedure. Abbreviations as in Figure 1.

(32,38). Because the effect of clopidogrel is time-dependent and dose-dependent, a tailored administration may be helpful to reduce the incidence of bleeding complications. Kon et al. (32) in a hybrid series of 15 patients administered 300 mg clopidogrel on arrival in the intensive care unit. However, they did not reverse heparin at the end of the surgery. The investigators report a mean of 0.2 ± 0.4 blood unit/patient transfusion rate, no re-exploration for bleeding, and no stent thrombosis.

The effect of reversal of heparin on stent patency is unknown. When CABG is performed on-pump, the antiplatelet effects of cardiopulmonary bypass may help prevent stent thrombosis. However when CABG is performed off-pump, the effects of heparin reversal are unknown. Because off-pump coronary artery bypass (OPCAB) has been reported to be associated with increased state of hypercoagulability (32), this coupled with a lower dose of clopidogrel to attempt to limit bleeding at the time of CABG may increase the likelihood of stent thrombosis. More data are needed to make firm recommendations.

OPCAB Versus MIDCAB

The number of hybrid (MIDCAB/PCI) procedures in some centers has decreased over an increase of OPCAB procedures (28). The OPCAB procedure compared with on-pump surgery has lower blood utilization, lower mortality in some high-risk patients (46), and lower costs (47). The Beating Heart Against Cardioplegic Arrest trial (48) has shown 2% mortality and a TLR rate of 2% at 2 years. Another trial (47) has confirmed low TLR rates (3.4%) and high graft patency rates (91%) at 1 year. Although OPCAB has lower costs compared with hybrid procedures and a 2-staged hybrid procedure requires 2 procedures and 2 hospital fees, and the need for potential repeat revascularization may be higher because of stent restenosis (22), MIDCAB procedures remain appealing. With minimal cardiac manipulation, the LIMA–LAD graft can be constructed and this can be done safely in patients with low ventricular ejection fraction with avoidance of aortic manipulation and of side-bite clamping used to construct the proximal anastomosis. Another potential benefit is avoidance of use of SVG, which limits the longevity of CABG surgery. It is likely that as technology improves the durability of DES, SVGs will become less ideal. We envision a hierarchy of value of revascularization choices: all high-grade proximal LAD lesions should probably be treated with a LIMA–LAD. After that, depending on the location and complexity of the lesion, a right internal mammary artery graft, a DES, SVG, BMS, or medical therapy alone may be preferable. Furthermore, some centers have reported diminished SVG patency rates after OPCAB, citing the hypercoagulability status in OPCAB to explain this phenomenon (49). This may make hybrid CABG/PCI more appealing.

Hybrid Valve/PCI

Alternative approaches to standard sternotomy for valve surgery have been advocated to reduce operative mortality and morbidity, speed recovery, and improve cosmetics. These approaches include partial sternotomies (50) and mini-thoracotomies (51). Concomitant coronary artery dis-

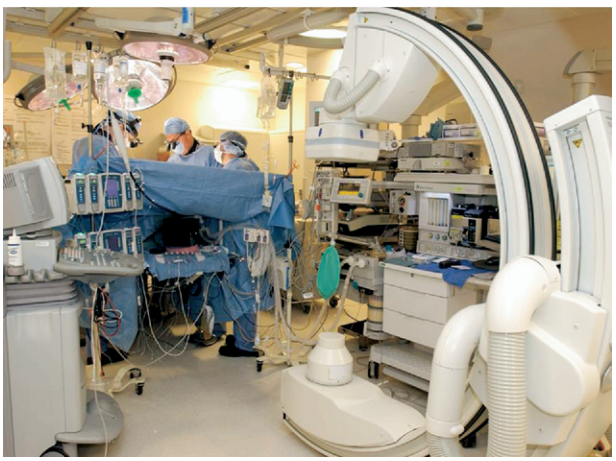

Figure 3. Hybrid Operating Room

A hybrid operating room.

ease has been a contraindication to such approaches because concomitant CABG, and therefore sternotomy, would be mandatory. Approaching coronary disease with PCI, which may actually be superior to SVG, has given the opportunity to expand the indications for minimally invasive valve surgery to patients with concomitant coronary disease.

Minimally Invasive Versus Conventional Valve Surgery

Minimally invasive valve surgery refers to a collection of techniques in which several alternative incisions to sternotomy (Fig. 4A) have been used. For minimally invasive aortic valve surgery, upper hemi-sternotomy (Fig. 4C) is the current standard (52,53). For mitral valve surgery, 2 approaches are used, including small right mini-thoracotomy (Fig. 4B) or lower hemisternotomy (Fig. 4D) (50,51,54). The robotic and video-assisted mitral valve procedure can be performed through a right mini-thoracotomy approach (55). Few cases have been reported for robotic aortic valve surgery (56).

To provide extrathoracic cardiopulmonary bypass, for peripheral cannulation or direct aortic cannulation, specialized arterial and venous cannulas are needed; for antegrade or retrograde cardioplegia, special endovascular cannulas and catheters are needed; and for aortic cross-clamp, specially designed endovascular aortic occlusion or transthoracic aortic cross-clamp are needed (50–52,55,57).

Large series of minimally invasive aortic and mitral valve surgery have reported reduced postoperative pain, faster recovery, less utilization of autologous blood, and superior cosmetic results (50–54). Reports that have compared minimally invasive valve surgery and conventional surgery have documented relatively consistent reduction in blood utilization and shorter hospital stay (52,58–60).

Because of the aforementioned benefits of minimally invasive valve surgery, recently some groups have combined minimally invasive valve surgery with PCI for combined valve/CABG surgery (45,54,57).

Rationale of Hybrid Valve/PCI

The rationale behind hybrid valve surgery is to substitute PCI for CABG (typically substituting PCI for SVG) to convert a combined valve/CABG procedure requiring sternotomy into an isolated valve procedure, which can be performed using minimally invasive techniques. We see 3 settings in which this may be of benefit.

CABG patient with poor conduit for CABG surgery. Poor or limited vein graft quality combined with poor target vessel quality is one of the reasons SVG failure at 1 year is as high as 30% (61). In the presence of such conditions, a PCI with DES may be a better option.

Convert high-risk valve/CABG surgery into a lower-risk isolated valve. Traditional valve/CABG surgery has twice the mortality of isolated valve surgery (62,63). In a large series of patients from the New York Cardiac Surgery Reporting System from 2001 to 2003 on approximately 10,000 patients, the mortality for isolated valve surgery was 4.4% versus 9% for valve and concomitant coronary surgery (62). In high-risk patients with multiple comorbidities such as increased age, low ejection fraction, morbid obesity, and pulmonary and renal dysfunction, it may even be higher. Thus, combining 2 low-risk strategies, PCI (1% mortality in the elective settings) with minimally invasive approaches (0.7% to 2% mortality range) (50) is very appealing to

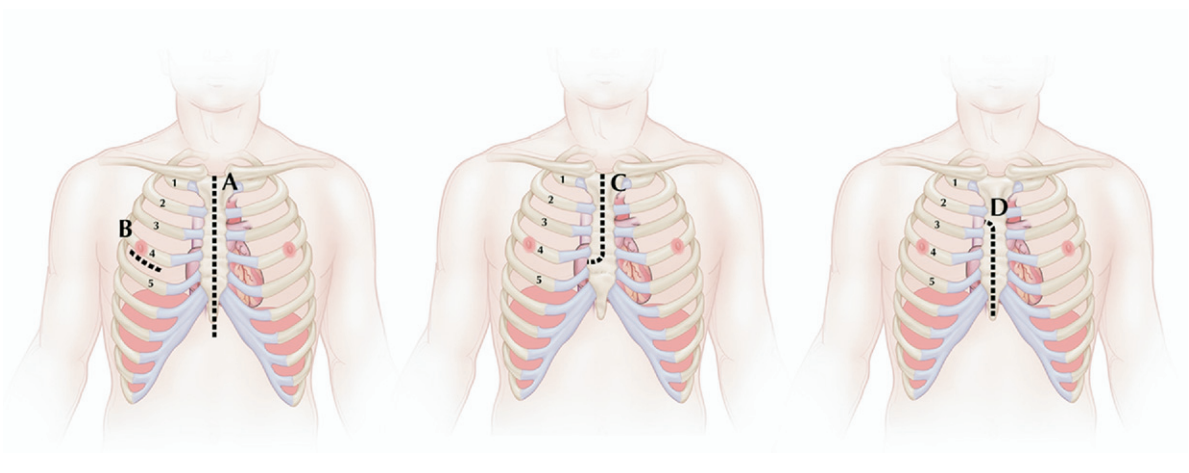

Figure 4. Incisions for Valve Surgery

(A) Median sternotomy (aortic, mitral, or tricuspid valve). **(B)** Right thoracotomy (mitral or tricuspid valve). **(C)** Upper hemi-sternotomy (aortic valve). **(D)** Lower hemi-sternotomy (mitral or tricuspid valve). Figure illustration by Rob Flewell.

reduce the overall operative risk (45). Brinster et al. (57) reported on 18 patients, mean age 76 years, with combined coronary artery and aortic valve disease. Avoiding high-risk CABG/valve surgery in this high-risk elderly population, a strategy of PCI with DES followed within 24 h by minimally invasive aortic valve replacement was used. The investigators report 5.5% in-hospital mortality and 95% patient survival at 19-month follow-up.

Hybrid valve surgery is especially suitable for patients with acute coronary syndrome and known valve disease. In this approach, usually PCI is performed first to the culprit lesion, stabilizing the coronary lesion, and then, during the same hospital stay, the valve lesion is addressed 5 to 7 days after the initial PCI (45). This approach converts an emergent/urgent concomitant coronary and valve surgery into a more elective isolated valve surgery. We reported on this approach in 26 patients with known combined coronary artery disease and valve disease. Of these patients, 92% had acute coronary syndrome, 50% had unstable angina, 42% had acute myocardial infarction, and 15% were in cardiogenic shock. The predicted Society of Thoracic Surgeons mortality, had conventional valve/CABG been performed at the time of PCI, for this group was 22%. The observed mortality was instead only 3.8% (45).

Convert reoperative valve/CABG into reoperative isolated valve surgery. Two broad scenarios for this strategy include the need for reoperative valve re-replacement for structural valve degenerations after biological valve replacement in the setting of known coronary disease and the need for primary native valve surgery late after CABG. Typical scenarios for the latter include late native aortic valve stenosis after CABG in which the gradient at the time of original CABG was thought to not warrant concomitant aortic valve replacement (64) or late ischemic mitral regurgitation after CABG in which avoiding sternotomy is particularly appealing. Both these sets of patients typically have a patent LIMA–LAD graft, which makes resternotomy particularly hazardous. The benefits of a hybrid approach are to perform PCI to a graft or native vessel coronary artery disease, thereby avoiding the reoperative CABG component. It just makes no sense to dissect the entire heart, placing patent grafts at risk, to place an SVG on an obtuse marginal target. In valvular patients, because of the cardiomegaly which can make the heart closer to the posterior table of the sternum by displacing it anteriorly, the re-entry has a 4% incidence of complication (65). Moreover, the exposure of the mitral valve in redo sternotomy can be difficult because the heart is fixed anteriorly and cannot drop into the left chest, and in the presence of a prosthetic aortic valve, the fibrous skeleton is fixed and the heart cannot be rotated, making exposure very difficult and limited. With the minimally invasive right thoracotomy approach, the visualization of the mitral valve is excellent (54).

In patients with previous bypass grafts, careful dissection to avoid injury to a patent LIMA–LAD graft is necessary because of the high mortality (50%) that such a complication carries (66). Embolization to the native coronary system of manipulated diseased but patent SVGs increases mortality and morbidity (67). Overall, reoperative surgery, unless for isolated aortic valve surgery, has an increased risk of mortality, morbidity, sternal dehiscence, and bleeding (65,68).

Limitations of Hybrid Valve/PCI

As for coronary hybrid CABG/PCI, there is concern regarding the impact of antiplatelet agents on bleeding after surgery. In the literature, one hybrid valve series (45) reports increased chest tube output, blood requirements (85% of patients received a blood transfusion), and reoperation for bleeding (8%), whereas another series (57) reports low chest tube output, low incidence of reoperation for bleeding (0%), and lower blood utilization (44% of patients). Both series are retrospective studies with small numbers of patients. The main difference between these series is the timing of the surgery, in the first within 5 to 7 days after PCI and in the second within 24 h. It may be hypothesized that the different timing of loading of clopidogrel has an impact on the different incidence of bleeding. Another way to decrease the risk of bleeding is to shorten the staging of PCI and surgery within 6 h, so that clopidogrel effects are just beginning to take effect once the surgery is completed. This approach, however, requires a specially designed suite, the hybrid operating room (Fig. 3), because if performed in 2 separate suites, it will require holding an operating room and double fee for the catheter laboratory and the operating room. We have performed 31 1-stop hybrid valve/PCI procedures (unpublished data) in our hybrid suite, with improved mortality rates compared to the Society of Thoracic Surgeons predicted outcomes. Finally, if significant proximal LAD disease is present, the patient should probably undergo LIMA–LAD and valve surgery via a conventional sternotomy. If the patient is so high-risk that sternotomy is thought contraindicated, PCI to the LAD combined with minimally invasive valve surgery is probably reasonable.

Limitations of minimally invasive valve surgery are: the need for a learning curve; operative times can be longer, especially at the beginning; it requires the surgeon to work through smaller incisions with sometimes different instruments than usual; and the exposure of the valve can be initially difficult. Moreover, the institution of cardiopulmonary bypass and myocardial protection can be more time consuming and troublesome. Satisfactory de-airing may be difficult because of the limited access to the aorta or the apex of the heart. This has raised concern among some investigators of increased risk of neurological adverse events (69). Another concern is the inability to fully

JACC: CARDIOVASCULAR INTERVENTIONS, VOL. 1, NO. 5, 2008
OCTOBER 2008:459–68

visualize the heart in case of heart distension, thus relying almost completely on transesophageal echocardiogram to monitor heart distension.

Hybrid Atrial Fibrillation Procedures: Combined Endocardial/Epicardial Approach

Surgical treatment of AF is usually reserved for patients undergoing either valve or coronary surgery. Lesions sets are created either surgically with incisional atriotomies (the Maze procedure) (70) or through epicardial or endocardial ablation. The latter can be achieved though cryoablation or radiofrequency.

Isolated treatment for AF is usually pharmacological or catheter-based ablation, or a combination of both for resistant AF (71). Further development of the closed-chest or minimally invasive technique by surgeons has expanded the horizon to lone epicardial atrial fibrillation surgery, perhaps in conjunction with percutaneous endocardial techniques. The surgical approaches have the advantages of being faster and more extensive than percutaneous approaches. However, some lesions may be more easily created by percutaneous approach. Ideally, this would be done in a specially designed hybrid electrophysiologist operating room to further modify treatment or to assess effects of lesions created (72). Some groups already have been using this strategy in a staged fashion (73).

Hybrid Approach for Complex Thoracic Aortic Aneurysms: Debranching Procedures Combined With Endovascular Stenting

Currently, the treatment of complex thoracic aneurysms is mostly endovascular, whereas traditionally, open repair is reserved for cases that are not suitable for endovascular stenting because of anatomic characteristics of the aneurysm. A combination of surgical and endovascular treatment is reserved for a highly selected group of patients who are too high-risk for surgical open repair and have inadequate length of the landing zone (distal or proximal) for deployment of endovascular stenting. In the treatment of aortic arch aneurysm, an aorto-innominate bypass is typically constructed followed by bypass of the head vessels of this graft, which allows proximal extension of stent grafts into the transverse aortic arch. The feasibility of such procedures has been reported with acceptable mortality and morbidity, albeit with a higher incidence of early endovascular leaks (74–76). The natural history of these endovascular leaks seems favorable, with high resolution at 6 months of follow-up (90%).

More often debranching procedures are used to treat complex thoracoabdominal aneurysms. In these hybrid procedures, bypasses and/or transposition of visceral vessels are used to enable distal extension in the visceral portion of the aorta of the stent graft. Experienced centers report a high periprocedural success rate (90%) with acceptable mortality rates (between 3% and 24%, average of 13%) (77–80). These procedures are long and complex, and there is concern regarding the long-term patency of prosthetic grafts used for visceral and renal revascularization (80).

Conclusions

Hybrid CABG/PCI is performed in only few centers, but may experience renewed interest as technology makes DES better than SVG. Hybrid CABG/PCI may be reserved for higher-risk patients who are not candidates for conventional CABG. In these patients, a MIDCAB with LIMA–LAD and PCI to non-LAD vessels may help reduce risk. With the advent of DES and lower stent restenosis rate compared with BMS, DES may be a valid alternative to SVGs as the overall patency rate is superior at 1 year for the DES.

Hybrid valve/PCI represents an excellent alternative to conventional valve/CABG in some high-risk patients, particularly those who presents after acute coronary syndromes, and in some patients who require reoperative valve surgery.

Hybrid atrial fibrillation treatments combine percutaneous endomyocardial and surgical epicardial approaches. Some centers have already tried to combine surgical and percutaneous ablation in a staged fashion. There may be a role for a hybrid electrophysiologist laboratory for these procedures to be performed in 1 setting with intraoperative mapping.

Aortic debranching procedures enable deployment of endovascular stents with inadequate length of the landing zone. Frequently, these patients are high-risk candidates for the performance of open surgical intervention and because of aneurysm anatomy are not candidate for endovascular repair. More commonly, these procedures are reserved for the treatment of complex thoracoabdominal aneurysm.

The future of cardiac surgery and interventional cardiology is headed toward a merger of the fields for tailored approaches to patients who present with complex heart disease. Although the ability to offer hybrid approaches will depend on technological advancements, improved percutaneous and minimally invasive techniques, and the availability of a hybrid suite, the true barrier to entry is the ability of cardiologists and cardiac surgeons to work together (81), to engage in "hybrid thinking" (82) with close collaboration between the 2 specialties. We believe the willingness and ability to create this collaborative culture is the largest barrier to creating a successful hybrid program. We are all cardiovascular interventionalists, with different tools.

Reprint requests and correspondence: Dr. John G. Byrne, Department of Cardiac Surgery, Vanderbilt University Medical Center, Nashville, Tennessee 37232-8802. E-mail: john.byrne@vanderbilt.edu.

REFERENCES

1. Angelini GD, Wilde P, Salerno TA, Bosco G, Calafiore AM. Integrated left small thoracotomy and angioplasty for multivessel coronary artery revascularisation. Lancet 1996;347:757–8.
2. Loulmet D, Carpentier A, d'Attellis N, et al. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. J Thorac Cardiovasc Surg 1999;118:4–10.
3. Farhat F, Depuydt F, Praet FV, Coddens J, Vanermen H. Hybrid cardiac revascularization using a totally closed-chest robotic technology and a percutaneous transluminal coronary dilatation. Heart Surg Forum 2000;3:119–20, discussion 120–2.
4. Hoffman SN, TenBrook JA, Wolf MP, Pauker SG, Salem DN, Wong JB. A meta-analysis of randomized controlled trials comparing coronary artery bypass graft with percutaneous transluminal coronary angioplasty: one- to eight-year outcomes. J Am Coll Cardiol 2003;41:1293–304.
5. Bravata DM, Gienger AL, McDonald KM, et al. Systematic review: the comparative effectiveness of percutaneous coronary interventions and coronary artery bypass graft surgery. Ann Intern Med 2007;147:703–16.
6. Hannan EL, Wu C, Walford G, et al. Drug-eluting stents vs. coronary-artery bypass grafting in multivessel coronary disease. N Engl J Med 2008;358:331–41.
7. Alexander JH, Hafley G, Harrington RA, et al. Efficacy and safety of edifoligide, an E2F transcription factor decoy, for prevention of vein graft failure following coronary artery bypass graft surgery: PREVENT IV: a randomized controlled trial. JAMA 2005;294:2446–54.
8. The BARI Investigators. The final 10-year follow-up results from the BARI randomized trial. J Am Coll Cardiol 2007;49:1600–6.
9. Kim KB, Cho KR, Jeong DS. Midterm angiographic follow-up after off-pump coronary artery bypass: serial comparison using early, 1-year, and 5-year postoperative angiograms. J Thorac Cardiovasc Surg 2008;135:300–7.
10. Hayward PA, Buxton BF. Contemporary coronary graft patency: 5-year observational data from a randomized trial of conduits. Ann Thorac Surg 2007;84:795–9.
11. Tatoulis J, Buxton BF, Fuller JA. Patencies of 2127 arterial to coronary conduits over 15 years. Ann Thorac Surg 2004;77:93–101.
12. Versaci F, Gaspardone A, Tomai F, Crea F, Chiariello L, Gioffre PA. A comparison of coronary-artery stenting with angioplasty for isolated stenosis of the proximal left anterior descending coronary artery. N Engl J Med 1997;336:817–22.
13. Kastrati A, Schomig A, Elezi S, et al. Predictive factors of restenosis after coronary stent placement. J Am Coll Cardiol 1997;30:1428–36.
14. Puskas JD, Williams WH, Mahoney EM, et al. Off-pump vs conventional coronary artery bypass grafting: early and 1-year graft patency, cost, and quality-of-life outcomes: a randomized trial. JAMA 2004;291:1841–9.
15. Balacumaraswami L, Taggart DP. Intraoperative imaging techniques to assess coronary artery bypass graft patency. Ann Thorac Surg 2007;83:2251–7.
16. Ashby DT, Dangas G, Mehran R, et al. Comparison of clinical outcomes using stents versus no stents after percutaneous coronary intervention for proximal left anterior descending versus proximal right and left circumflex coronary arteries. Am J Cardiol 2002;89:1162–6.
17. Weisz G, Leon MB, Holmes DR Jr., et al. Two-year outcomes after sirolimus-eluting stent implantation: results from the Sirolimus-Eluting Stent in de Novo Native Coronary Lesions (SIRIUS) trial. J Am Coll Cardiol 2006;47:1350–5.
18. Dangas G, Ellis SG, Shlofmitz R, et al. Outcomes of paclitaxel-eluting stent implantation in patients with stenosis of the left anterior descending coronary artery. J Am Coll Cardiol 2005;45:1186–92.
19. Sawhney N, Moses JW, Leon MB, et al. Treatment of left anterior descending coronary artery disease with sirolimus-eluting stents. Circulation 2004;110:374–9.
20. Lloyd CT, Calafiore AM, Wilde P, et al. Integrated left anterior small thoracotomy and angioplasty for coronary artery revascularization. Ann Thorac Surg 1999;68:908–11, discussion 911–2.
21. Isomura T, Suma H, Horii T, Sato T, Kobashi T, Kanemitsu H. Minimally invasive coronary artery revascularization: off-pump bypass grafting and the hybrid procedure. Ann Thorac Surg 2000;70:2017–22.
22. de Canniere D, Jansens JL, Goldschmidt-Clermont P, Barvais L, Decroly P, Stoupel E. Combination of minimally invasive coronary bypass and percutaneous transluminal coronary angioplasty in the treatment of double-vessel coronary disease: two-year follow-up of a new hybrid procedure compared with "on-pump" double bypass grafting. Am Heart J 2001;142:563–70.
23. Presbitero P, Nicolini F, Maiello L, et al. "Hybrid" percutaneous and surgical coronary revascularization: selection criteria from a single-center experience. Ital Heart J 2001;2:363–8.
24. Cisowski M, Morawski W, Drzewiecki J, et al. Integrated minimally invasive direct coronary artery bypass grafting and angioplasty for coronary artery revascularization. Eur J Cardiothorac Surg 2002;22:261–5.
25. Stahl KD, Boyd WD, Vassiliades TA, Karamanoukian HL. Hybrid robotic coronary artery surgery and angioplasty in multivessel coronary artery disease. Ann Thorac Surg 2002;74:S1358–62.
26. Lewis BS, Porat E, Halon DA, et al. Same-day combined coronary angioplasty and minimally invasive coronary surgery. Am J Cardiol 1999;84:1246–7.
27. Wittwer T, Cremer J, Klima U, Wahlers T, Haverich A. Myocardial "hybrid" revascularization: intermediate results of an alternative approach to multivessel coronary artery disease. J Thorac Cardiovasc Surg 1999;118:766–7.
28. Riess FC, Bader R, Kremer P, et al. Coronary hybrid revascularization from January 1997 to January 2001: a clinical follow-up. Ann Thorac Surg 2002;73:1849–55.
29. Zenati M, Cohen HA, Griffith BP. Alternative approach to multivessel coronary disease with integrated coronary revascularization. J Thorac Cardiovasc Surg 1999;117:439–44, discussion 444–6.
30. Us MH, Basaran M, Yilmaz M, et al. Hybrid coronary revascularization in high-risk patients. Tex Heart Inst J 2006;33:458–62.
31. Gilard M, Bezon E, Cornily JC, et al. Same-day combined percutaneous coronary intervention and coronary artery surgery. Cardiology 2007;108:363–7.
32. Kon ZN, Brown EN, Tran R, et al. Simultaneous hybrid coronary revascularization reduces postoperative morbidity compared with results from conventional off-pump coronary artery bypass. J Thorac Cardiovasc Surg 2008;135:367–75.
33. Lee MS, Wilentz JR, Makkar RR, et al. Hybrid revascularization using percutaneous coronary intervention and robotically assisted minimally invasive direct coronary artery bypass surgery. J Invasive Cardiol 2004;16:419–25.
34. Davidavicius G, Van Praet F, Mansour S, et al. Hybrid revascularization strategy: a pilot study on the association of robotically enhanced minimally invasive direct coronary artery bypass surgery and fractional-flow-reserve-guided percutaneous coronary intervention. Circulation 2005;112:I317–22.
35. Kiaii B, McClure RS, Kostuk WJ, et al. Concurrent robotic hybrid revascularization using an enhanced operative suite. Chest 2005;128:4046–8.
36. Katz MR, Van Praet F, de Canniere D, et al. Integrated coronary revascularization: percutaneous coronary intervention plus robotic totally endoscopic coronary artery bypass. Circulation 2006;114:I473–6.
37. Vassiliades TA Jr., Douglas JS, Morris DC, et al. Integrated coronary revascularization with drug-eluting stents: immediate and seven-month outcome. J Thorac Cardiovasc Surg 2006;131:956–62.
38. Bonatti J, Schachner T, Bonaros N, et al. Simultaneous Hybrid COronary Revascularization Using Totally Endoscopic Left Internal Mammary Artery Bypass Grafting and Placement of RapamycIN Eluting Stents in the SAme IntervenTIONal Session. The COMBINATION Pilot Study. Cardiology 2007;110:92–5.

39. Gersbach P, Imsand C, von Segesser LK, Delabays A, Vogt P, Stumpe F. Beating heart coronary artery surgery: is sternotomy a suitable alternative to minimal invasive technique? Eur J Cardiothorac Surg 2001;20:760–4.
40. Morice MC, Serruys PW, Barragan P, et al. Long-term clinical outcomes with sirolimus-eluting coronary stents: five-year results of the RAVEL trial. J Am Coll Cardiol 2007;50:1299–304.
41. Camenzind E, Steg PG, Wijns W. Stent thrombosis late after implantation of first-generation drug-eluting stents: a cause for concern. Circulation 2007;115:1440–55, discussion 1455.
42. Nordmann AJ, Briel M, Bucher HC. Mortality in randomized controlled trials comparing drug-eluting vs. bare metal stents in coronary artery disease: a meta-analysis. Eur Heart J 2006;27:2784–814.
43. Stone GW, Moses JW, Ellis SG, et al. Safety and efficacy of sirolimus- and paclitaxel-eluting coronary stents. N Engl J Med 2007;356:998–1008.
44. Serruys PW, Emanuelsson H, van der Giessen W, et al. Heparin-coated Palmaz-Schatz stents in human coronary arteries. Early outcome of the Benestent-II Pilot Study. Circulation 1996;93:412–22.
45. Byrne JG, Leacche M, Unic D, et al. Staged initial percutaneous coronary intervention followed by valve surgery ("hybrid approach") for patients with complex coronary and valve disease. J Am Coll Cardiol 2005;45:14–8.
46. Ascione R, Narayan P, Rogers CA, Lim KH, Capoun R, Angelini GD. Early and midterm clinical outcome in patients with severe left ventricular dysfunction undergoing coronary artery surgery. Ann Thorac Surg 2003;76:793–9.
47. Nathoe HM, van Dijk D, Jansen EW, et al. A comparison of on-pump and off-pump coronary bypass surgery in low-risk patients. N Engl J Med 2003;348:394–402.
48. Angelini GD, Taylor FC, Reeves BC, Ascione R. Early and midterm outcome after off-pump and on-pump surgery in Beating Heart Against Cardioplegic Arrest Studies (BHACAS 1 and 2): a pooled analysis of two randomised controlled trials. Lancet 2002;359:1194–9.
49. Kim KB, Lim C, Lee C, et al. Off-pump coronary artery bypass may decrease the patency of saphenous vein grafts. Ann Thorac Surg 2001;72:S1033–7.
50. Soltesz EG, Cohn LH. Minimally invasive valve surgery. Cardiol Rev 2007;15:109–15.
51. Grossi EA, Galloway AC, LaPietra A, et al. Minimally invasive mitral valve surgery: a 6-year experience with 714 patients. Ann Thorac Surg 2002;74:660–3, discussion 663–4.
52. Dogan S, Dzemali O, Wimmer-Greinecker G, et al. Minimally invasive versus conventional aortic valve replacement: a prospective randomized trial. J Heart Valve Dis 2003;12:76–80.
53. Tabata M, Umakanthan R, Cohn LH, et al. Early and late outcomes of 1000 minimally invasive aortic valve operations. Eur J Cardiothorac Surg 2008;33:537–41.
54. Umakanthan R, Leacche M, Petracek MR, et al. Safety of minimally invasive mitral valve surgery without aortic cross-clamp. Ann Thorac Surg 2008;85:1544–9, discussion 1549–50.
55. Nifong LW, Chitwood WR, Pappas PS, et al. Robotic mitral valve surgery: a United States multicenter trial. J Thorac Cardiovasc Surg 2005;129:1395–404.
56. Folliguet TA, Vanhuyse F, Konstantinos Z, Laborde F. Early experience with robotic aortic valve replacement. Eur J Cardiothorac Surg 2005;28:172–3.
57. Brinster DR, Byrne M, Rogers CD, et al. Effectiveness of same day percutaneous coronary intervention followed by minimally invasive aortic valve replacement for aortic stenosis and moderate coronary disease ("hybrid approach"). Am J Cardiol 2006;98:1501–3.
58. Sharony R, Grossi EA, Saunders PC, et al. Propensity score analysis of a six-year experience with minimally invasive isolated aortic valve replacement. J Heart Valve Dis 2004;13:887–93.
59. Grossi EA, LaPietra A, Ribakove GH, et al. Minimally invasive versus sternotomy approaches for mitral reconstruction: comparison of intermediate-term results. J Thorac Cardiovasc Surg 2001;121:708–13.
60. Bakir I, Casselman FP, Wellens F, et al. Minimally invasive versus standard approach aortic valve replacement: a study in 506 patients. Ann Thorac Surg 2006;81:1599–604.
61. Magee MJ, Alexander JH, Hafley G, et al. Coronary artery bypass graft failure after on-pump and off-pump coronary artery bypass: findings from PREVENT IV. Ann Thorac Surg 2008;85:494–9, discussion 499–500.
62. Hannan EL, Wu C, Bennett EV, et al. Risk index for predicting in-hospital mortality for cardiac valve surgery. Ann Thorac Surg 2007;83:921–9.
63. van Gameren M, Kappetein AP, Steyerberg EW, et al. Do we need separate risk stratification models for hospital mortality after heart valve surgery? Ann Thorac Surg 2008;85:921–30.
64. Collins JJ Jr., Aranki SF. Management of mild aortic stenosis during coronary artery bypass graft surgery. J Card Surg 1994;9:145–7.
65. Lytle BW, Cosgrove DM, Taylor PC, et al. Reoperations for valve surgery: perioperative mortality and determinants of risk for 1,000 patients, 1958–1984. Ann Thorac Surg 1986;42:632–43.
66. Dobell AR, Jain AK. Catastrophic hemorrhage during redo sternotomy. Ann Thorac Surg 1984;37:273–8.
67. Grondin CM, Pomar JL, Hebert Y, et al. Reoperation in patients with patent atherosclerotic coronary vein grafts. A different approach to a different disease. J Thorac Cardiovasc Surg 1984;87:379–85.
68. Potter DD, Sundt TM 3rd, Zehr KJ, et al. Operative risk of reoperative aortic valve replacement. J Thorac Cardiovasc Surg 2005;129:94–103.
69. Svensson LG, Gillinov AM, Blackstone EH, et al. Does right thoracotomy increase the risk of mitral valve reoperation? J Thorac Cardiovasc Surg 2007;134:677–82.
70. Cox JL. Surgical treatment of atrial fibrillation: a review. Europace 2004;5 Suppl 1:S20–9.
71. Saksena S, Madan N. Hybrid therapy of atrial fibrillation: algorithms and outcome. J Interv Card Electrophysiol 2003;9:235–47.
72. Skanes AC, Klein GJ, Guiraudon G, et al. Hybrid approach for minimally-invasive operative therapy of arrhythmias. J Interv Card Electrophysiol 2003;9:289–94.
73. Bisleri G, Curnis A, Bottio T, Mascioli G, Muneretto C. The need of a hybrid approach for the treatment of atrial fibrillation. Heart Surg Forum 2005;8:E326–30.
74. Melissano G, Bertoglio L, Civilini E, et al. Results of thoracic endovascular grafting in different aortic segments. J Endovasc Ther 2007;14:150–7.
75. Bergeron P, Mangialardi N, Costa P, et al. Great vessel management for endovascular exclusion of aortic arch aneurysms and dissections. Eur J Vasc Endovasc Surg 2006;32:38–45.
76. Saleh HM, Inglese L. Combined surgical and endovascular treatment of aortic arch aneurysms. J Vasc Surg 2006;44:460–6.
77. Bockler D, Kotelis D, Geisbusch P, et al. Hybrid procedures for thoracoabdominal aortic aneurysms and chronic aortic dissections—a single center experience in 28 patients. J Vasc Surg 2008;47:724–32.
78. Black SA, Wolfe JH, Clark M, Hamady M, Cheshire NJ, Jenkins MP. Complex thoracoabdominal aortic aneurysms: endovascular exclusion with visceral revascularization. J Vasc Surg 2006;43:1081–9, discussion 1089.
79. Zhou W, Reardon M, Peden EK, Lin PH, Lumsden AB. Hybrid approach to complex thoracic aortic aneurysms in high-risk patients: surgical challenges and clinical outcomes. J Vasc Surg 2006;44:688–93.
80. Lee WA, Brown MP, Martin TD, Seeger JM, Huber TS. Early results after staged hybrid repair of thoracoabdominal aortic aneurysms. J Am Coll Surg 2007;205:420–31.
81. King SB 3rd. Who are interventionalists? What about surgeons? J Am Coll Cardiol Intv 2008;1:109–10.
82. Friedrich GJ, Bonatti J. Hybrid coronary artery revascularization—review and update 2007. Heart Surg Forum 2007;10:E292–6.

Key Words: hybrid procedures ■ minimally invasive cardiac surgery ■ percutaneous coronary intervention.