Background—Aortic valve bypass (AVB; apicoaortic conduit) surgery relieves aortic stenosis (AS) by shunting blood from the apex of the left ventricle to the descending thoracic aorta through a valved conduit. We have performed AVB surgery as an alternative to conventional aortic valve replacement for high-risk AS patients.

Methods and Results—Between 2003 and 2007, 31 high-risk AS patients were treated with AVB surgery. Twenty-two patients (71%) were undergoing reoperation with patent coronary bypass grafts, and 5 (16%) had a porcelain ascending aorta. The average age was 81 years. Cardiopulmonary bypass was used for 19 of 31 patients (61%); the median duration of cardiopulmonary bypass was 19 minutes. Cross-clamp time for all patients was 0 minutes. Perioperative mortality was 13% (4 of 31 patients); no perioperative deaths occurred in the last 16 consecutive patients. One patient experienced a stroke related to intraoperative hypotension. No strokes have occurred during follow-up. Renal function was unchanged after AVB (preoperative creatinine, 1.3–0.5 mg/dL; postoperative creatinine, 1.2–0.5 mg/dL). The mean gradient across the native aortic valve decreased from 43.5–15 to 10.4–5.4 mm Hg. Echocardiographically determined conduit flow expressed as a percentage of total cardiac output was 72–12%.

Conclusions—AVB surgery is an important therapeutic option for high-risk patients with symptomatic AS. Ventricular outflow is distributed in a predictable fashion between the conduit and the left ventricular outflow tract, and AVB surgery reliably relieves AS. Stroke and renal dysfunction were uncommon. (Circulation. 2008;118:1460-1466.)

Key Words: aorta ■ stenosis ■ surgery ■ valves

Aortic valve replacement (AVR) has afforded relief of symptoms and prolongation of life for millions of patients with valvular aortic stenosis (AS). Outcomes after conventional AVR, although clearly superior to the natural history of untreated AS,1 remain imperfect. AVR mandates the use of cardiopulmonary bypass, ascending aortic cross-clamping, aortotomy, debridement of the diseased valve, and cardioplegic cardiac arrest; it therefore carries a finite risk of morbidity and mortality, particularly in the elderly1,2 and those with significant comorbidities.3,4 Recent recognition that almost 60% of patients with symptomatic AS are never referred to surgery as a result of actual and perceived risks has fueled interest in alternatives (such as expandable metallic stent-mounted valve implantation) to conventional AVR for the treatment of AS.5–8

Clinical Perspective p 1466

As an alternative to conventional AVR for high-risk and “inoperable” patients, we have refocused efforts on an established but uncommonly used surgical procedure for relief of left ventricular outflow tract obstruction associated with valvular AS: aortic valve bypass (AVB) surgery. An AVB (apicoaortic conduit) is a conduit containing a prosthetic valve that relieves AS by shunting blood from the apex of the left ventricle to the descending thoracic aorta (Figure 1). AVB surgery was first reported in animal models in 1955, with several long-term survivors.9 The first successful clinical case was done in 1962.10 AVB surgery was then eclipsed by conventional orthotopic AVR in the early 1960s. Interest was refocused on AVB surgery in the 1970s in the laboratories of Glenn Morrow at the National Institutes of Health with the intent of relieving complex congenital left ventricular outflow tract obstruction in children. Brown (personal communication, John W. Brown, MD, 2008) developed the apical connector that is used clinically for AVB surgery today. Although the Ross-Kono procedure is now used for children with complex left ventricular outflow tract obstruction,11 AVB surgery has been applied sporadically to high-risk adult patients with acquired AS, with just over 100 reported cases in the literature.12

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Beginning in 2003, we initiated a concentrated clinical experience in AVB surgery for high-risk AS patients at the University of Maryland. The purposes of this article are to update our clinical experience, to characterize the hemodynamics of the circulation after construction of an AVB, to assess midterm outcomes, and to report lessons learned.

Methods
This retrospective chart review was approved by the Institutional Review Board of the University of Maryland Medical Center. The estimated mortality risk was calculated with the Society of Thoracic Surgeons validated risk model.

Preoperative Evaluation/Patient Selection
All patients underwent a thorough systematic preoperative evaluation that included left and right heart catheterization, multislice computed chest tomography, transesophageal echocardiography, and a careful clinical evaluation. Patients were excluded for consideration for AVB surgery if the degree of aortic insufficiency was greater than moderate. Mural calcification of the descending thoracic aorta was often detected by computed tomography and rarely was an exclusion criterion unless it was dense, concentric, and diffuse (ie, "porcelain"). Intramural descending thoracic aortic atherosclerotic disease also was commonly seen on transesophageal echocardiography and was not considered a contraindication to surgery.

Operative Technique
Construction of the AVB is done on the back table while the patient is positioned with the hips at a 45° angle and the chest in a lateral decubitus position. The conduit consists of 3 parts: a rigid stented apical connector with a sewing ring (Hancock apical left ventricle connector, model 174A, Medtronic Inc, Minneapolis, Minn; Figure 2) that is designed to be inserted into the apex of the left ventricle, a stentless porcine valve (Freestyle aortic root bioprosthesis, Medtronic Inc), and a woven Dacron graft with an 8-mm side branch. The coronary buttons on the valve are oversewn, and the components were anastomosed with running 4-0 monofilament suture. Early in the series, we used a nominal size 23 valve (and size 20 connector) in 4 patients and a size 19 valve (and size 16 connector) in 2 patients but now favor the use of a nominal size 18 apical connector, a size 21 Freestyle valve, and a 20-mm Dacron graft for all patients.

The left groin is opened, and a venous cannula (size 21 Bio- medicus, Medtronic Inc) is inserted using transesophageal echocardiographic guidance. We administer 5000 U heparin before cannulation. A sixth interspace small left lateral thoracotomy is performed after selective lung ventilation is initiated, and the descending thoracic aorta is exposed. To achieve adequate exposure of the apex of the heart, the sixth or seventh rib can be shingled medially. Accurate sizing and orientation of the conduit are crucial. Placement of a partial occluding clamp on the aorta allows construction of the distal anastomosis with running 4-0 monofilament suture. Once the clamp is released, the 8-mm side branch is connected to the arterial line of the cardiopulmonary bypass circuit. The apical pericardium is opened wide; the left ventricular apex is exposed; and an appropriate site for the apical anastomosis is identified. We have generally favored a location ~2 cm lateral to the true apex. Between 8 and 10 2-0 monofilament sutures with large Teflon pledgets are placed in a circumferential fashion around the apex and then threaded through the sewing ring on the apical connector. These sutures are placed deep in the myocardium (ie, nearly full thickness of the ventricular wall; Figure 3). With the patient in steep Trendelenburg position, a
stab wound is created in the apex, and a size 14 Foley catheter is inserted several centimeters and inflated to a size slightly larger than a circular coring knife (outer diameter, 0.69 in), and the apical myocardial plug is cored out. The apical connector is then rapidly inserted and tied in place, establishing blood flow through the newly created conduit. The graft is deaired with an 18-gauge needle, and the conduit is positioned so that it surrounds the left lower lobe in the costophrenic sulcus. Cardiopulmonary bypass is initiated during insertion of the apical connector at the surgeon’s discretion.

Postoperative Management
All patients were treated with 325 mg daily aspirin. Routine predischarge echocardiography and contrast-enhanced multislice computed tomography were performed.

Follow-Up
Follow-up was conducted at 1, 6, and 12 months by clinical examination or telephone interview and yearly thereafter. Follow-up ranged from 1.5 to 48 months, with a mean follow-up of 17 months. No patient was lost to follow-up.

Echocardiography
Patients underwent predessional echocardiography to assess cardiac performance and function of the AVB. Standard transthoracic echocardiography was performed in accordance with the American Society of Echocardiography’s standardized reporting recommendations. All echocardiographic studies were performed in the core echocardiography laboratory at the University of Maryland Medical Center. In addition to the standard clinical examination, the conduit was imaged from a modified apical or epigastric window, and velocity-time integrals were recorded for at least 10 beats. Stroke volumes were calculated for both the native left ventricular outflow tract and the conduit, and conduit flow was expressed as a percentage of total stroke volume.

Intraoperative Conduit Flow Assessment
After insertion of the AVB conduit into the apex of the ventricle and after return of hemodynamic stability, flow through the conduit was measured with an ultrasonic flow probe (model HT312-CS, 16-mm flow probe, Transonic Systems Inc, Ithaca, NY) applied to the Dacron graft. Simultaneous cardiac output determinations were calculated with a Swan-Ganz catheter. The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results
From April 2003 through November 2007, 31 patients underwent left ventricular apex to descending thoracic aortic AVB for symptomatic AS. These AVB procedures represented 6.6% (31 of 469) of all isolated aortic valve operations during the same period. This was a high-risk patient population with a mean age of 81 years (range, 62 to 91 years). Thirteen women (42%) and 18 men were included. The mean preoperative calculated Society of Thoracic Surgeons risk score was 9.3±4.5 (range, 3.5 to 21.3). AVB was chosen as an alternative to conventional AVR because of the presence of risk factors, including reoperation with patent coronary bypass grafts in 22 patients (71%) and a porcelain ascending aorta in 5 patients (16%). Eight patients had chronic obstructive pulmonary disease; 4 required home oxygen. Five patients (19%) had chronic renal insufficiency (defined as a history of renal failure or history of serum creatinine >2.0 mg/dL). Eleven patients (35%) had cerebrovascular disease, with 5 of those patients (16% of total patient population) having a history of a previous cerebrovascular accident or transient ischemic attack. Fourteen (45%) had a history of myocardial infarction. Other comorbidities included hypertension (n=25, 81%), dyslipidemia (n=24, 77%), and diabetes mellitus (n=11, 35%). Of the 31 patients, 13 (42%) had previously been refused for conventional cardiac surgery.

The mean preoperative aortic valve area was 0.65±0.25 cm² with a mean gradient of 44±15 mm Hg (range, 16 to 85 mm Hg) and a peak gradient of 70±27 (range, 30 to 134 mm Hg). The mean preoperative ejection fraction was 51±18% (range, 10% to 80%). The degree of aortic insufficiency was none to mild in 22 (71%) and moderate in 9 (29%). Mitral regurgitation was quantitated as none to trace in 3 patients (10%), mild in 13 (42%), moderate in 13 (42%), and severe in 2 (6%). Systolic pulmonary artery pressures averaged 43±17 mm Hg (range, 25 to 81 mm Hg).

Surgical Results
The myocardial ischemic time was 0 minutes for all patients. The mean procedural duration was 4 hours 16 minutes. Procedural times have decreased progressively from a mean of >5 hours in 2003 to 3 hours in 2007. Cardiopulmonary bypass was used for 19 of 31 patients (61%). The median perfusion time for patients for whom cardiopulmonary bypass was used was 19 minutes (Figure 4). As we have gained experience in inserting the apical connector on the beating heart, we are now able to perform AVB routinely without cardiopulmonary bypass.
One patient early in our experience developed cardiac tamponade and hypotension after chest closure in the operating room. Bleeding was controlled, but the patient sustained prolonged hypotension. He was found to have mild right leg weakness after extubation but was able to ambulate at the time of discharge. No patients have had a stroke in follow-up.

Perioperative mortality was 13% (4 of 31 patients) and occurred early in the series. One patient with advanced pulmonary fibrosis could not be oxygenated intraoperatively and died in the operating room. An autopsy confirmed advanced lung disease and a functioning AVB conduit. A second patient exsanguinated from an intraoperative lower gastrointestinal bleed at the conclusion of a technically uneventful AVB. The third in-hospital death was directly related to the insertion of the apical connector in the left ventricular apex. The sutures tore the myocardium, and hemostasis was achieved only after a prolonged bypass run. This patient died of multisystem organ failure on postoperative day 12. The fourth mortality occurred after hospital dismissal and was related to excessive anticoagulation with warfarin. This patient had a known history of pulmonary embolism and was discharged on the fifth hospital day after uneventful AVB surgery. Multiple pulmonary emboli were diagnosed 2 weeks later, and oral anticoagulation was instituted at another facility. He presented in cardiac arrest 3 weeks after surgery and was found to have an international normalized ratio of 11 and a massive lateral chest wall hematoma. The conduit was found to be intact at the time of emergency thoracotomy.

There have been no perioperative deaths in the last 16 consecutive patients.

Reoperations

There have been 9 reoperations in 6 patients. Two were for coagulopathic bleeding early after surgery, and 2 were early in our experience for apical pseudoaneurysms. Four patients have required thoracoscopic evacuation of blood from the left chest between 1 and 3 weeks after surgery. One patient (who required 2 reoperations for bleeding) developed an infected left pleural space; this infection was treated with decortication and a latissimus dorsi flap. She is in functional class I and has no evidence of infection 20 months after surgery. There have been no reoperations in the most recent 12 procedures.

The median ventilator time was 15 hours (range, 2 to 322 hours). Twenty-five patients (81%) were intubated for <24 hours. Tracheostomies were performed in 3 patients.

No patient developed a wound infection. No patient developed heart block requiring pacemaker insertion. One patient with a history of a previous renal transplant required temporary dialysis after AVB surgery but was discharged with satisfactory renal function. Renal function in all cases was well preserved; the creatinine before surgery (mean, 1.3±0.5 mg/dL; range, 0.6 to 2.6) was unchanged at discharge (mean, 1.2±0.5 mg/dL; range, 0.6 to 2.5).

Intraoperative graft flow measured with Doppler techniques averaged 2.3±0.6 L/min (range, 1.4 to 3.2 L/min), and simultaneous systemic cardiac output was 4.4±1.4 L/min (range, 2.5 to 7.7 L/min). Thus, acutely, blood flow through the graft was 58±23% of the total cardiac output.

Figure 5. Conduit flow expressed as a percentage of total stroke volume (mean, 72.1±12.0%). Relative flow was measured before hospital dismissal with quantitative Doppler echocardiography.

Median postoperative hospital length of stay for all patients was 10 days (range, 0 to 55 days). Quantitative Doppler echocardiography was performed before discharge on all operative survivors and demonstrated preserved ventricular function (postoperative ejection fraction, 53±18% compared with 51±18% before surgery). The postoperative mean gradient across the native stenotic aortic valve was 10.4±5.4 mm Hg (range, 3 to 23 mm Hg), a significant decrement from a mean preoperative value of 43.5±15 mm Hg.

Echocardiographically determined conduit flow expressed as a percentage of total cardiac output was 72±12% (range, 38% to 87%) (Figure 5). Mitral regurgitation was generally decreased after AVB surgery, with most patients experiencing a decrement in mitral regurgitation of 1 grade (Figure 6).

Late Complications

No patient developed conduit stenosis. There has been no clinical evidence of conduit infection. No conduit insufficiency has developed, and no patient has required late conduit reoperation. There have been no late strokes.

Survival

Follow-up ranged from 1.5 to 48 months, with a mean follow-up of 17 months. Postoperative survival is demonstrated graphically in Figure 7. No patient was lost to follow-up. Median postoperative survival was 870 days (29 months). Causes of late death in 12 patients included respiratory failure in 3 patients (all with working conduits), failure to thrive in 2 patients, cancer in 1 patient, and undetermined in 6 patients.

Discussion

This series supports AVB surgery as a valuable addition to the armamentarium of therapies for symptomatic AS, highlights an increased understanding of the physiology of a circulatory system with parallel left ventricular outflow tracts, reports technical advances that have permitted progressively
improved results, and generates hypotheses about the advantages of AVB surgery compared with other therapies for AS.

The patients in this series represent a small fraction of all patients having aortic valve surgery at our institution. They clearly belonged to the upper level of the risk spectrum as evidenced by their preoperative Society of Thoracic Surgeons risk scores, the presence of multiple comorbidities, and the high rate of refusal for conventional surgery. The vast majority either had a porcelain ascending aorta or required therapy for AS in the presence of functioning coronary bypass grafts, clinical scenarios that are recognized to be associated with significant morbidity and mortality and are not fully incorporated into current risk models. We found that construction of an AVB bypass conduit resulted in a predictable distribution of left ventricular stroke volume between the native (stenotic) left ventricular outflow tract and the newly placed conduit. On the basis of intraoperative flow probe and thermodilution catheter measurements, mean blood flow through the conduit represented 58% of the total cardiac output, whereas postoperative quantitative echocardiographic assessment demonstrated that a mean of 72% of cardiac output flowed through the AVB conduit. The discrepancy between these 2 measurements may be related to the time of measurement (intraoperative for the flow probe and thermodilution catheter versus postoperative for the echocardiographically determined flows) and to recognized inconsistencies in different techniques of cardiac output and blood flow measurements. Within each group, we found remarkable consistency from patient to patient (Figure 5).

AVB surgery reliably and effectively relieved the left ventricular outflow tract obstruction of acquired AS. We observed an echocardiographically determined mean gradient of 10 mm Hg across the native valve after AVB surgery, which is highly favorable and comparable to values reported for postoperative gradients after mechanical and bioprosthetic conventional AVR. Compared with conventional (orthotopic) AVR in which the effective orifice area of the left ventricular outflow tract after surgery is determined solely by the type and size of prosthesis chosen, the effective orifice area after AVB surgery is the sum of the native stenotic valve and the effective orifice area of the AVB conduit. Although patient prosthesis mismatch is a concern in conventional AVR surgery, particularly in patients with small aortic roots, the fact that a generous-diameter conduit (and bioprosthesis) can be placed in all patients undergoing AVB surgery obviates these concerns.

We found that relief of left ventricular outflow tract obstruction with an AVB conduit was commonly associated with a downgrading of the degree of mitral regurgitation. Thus, the presence of moderate mitral regurgitation has not dissuaded us from performing AVB surgery.

Left ventricular function is preserved after AVB surgery. Coring and removal of the apical plug of myocardium that permits insertion of the conduit did not have a detrimental effect on left ventricular function.

In this experience, AVB surgery had minimal adverse effects on renal function, with only 1 patient requiring temporary postoperative hemodialysis and all patients having excellent predischARGE renal function. This is in contrast to conventional AVR, in which renal failure has been reported in as many as 12% of elderly patients and is associated with a 41% mortality rate. Conventional AVR surgery is an independent predictor of the need for dialysis after cardiac surgery.
surgery.\textsuperscript{28} We believe that the lower risk of postoperative acute renal failure after AVB surgery is related to minimization or avoidance of cardiopulmonary bypass, the absence of ascending aortic cross-clamping, and minimization of non-pulsatile perfusion, all of which are recognized risk factors for acute renal failure after conventional AVR.\textsuperscript{29}

AVB surgery is technically challenging, and our data reflect a steep learning curve with progressively improved results. Specific technical aspects of the operation that have contributed to improved outcomes include precise sizing of the coring knife relative to the apical connector (the coring knife is ideally sized 10\% to 20\% smaller than the outer diameter of the connector to ensure a snug and hemostatic fit), recognition of the importance of placing the securing sutures deep (ie, nearly full thickness) in the myocardium, placement of the apical connector 2 cm lateral to the true apex, and proper anesthetic management. With the evolution of these improvements and increased experience, we have shown a marked reduction in apical insertion-related complications (pseudoaneurysms, perioperative bleeding, pleural space problems), decreased procedure times, and improved mortality. Although the overall mortality of this series was not markedly different from that predicted by the Society of Thoracic Surgeons risk model, we believe that the trend toward improved outcomes (no deaths among the last 16 patients and a markedly lower complication rate) suggests that a learning curve is present and that we have benefitted from progressive operative experience, including routine performance of AVB surgery without cardiopulmonary bypass.

The apex of the heart remains a formidable and sometimes friable structure, particularly in the elderly, and we believe that improved instrumentation (currently in development) will increase the safety of conduit insertion in the apex. Treatment of AS may evolve to a beating-heart operation that can be accomplished minimally invasively with 2 automated anastomoses.

Although our patient population was at high risk for perioperative neurological events, we observed only 1 stroke that was related to intraoperative hypotension. Furthermore, we did not detect any strokes in follow-up. Although this study is not adequately powered to draw definitive conclusions about the risk of stroke with AVB surgery compared with conventional AVR, we believe that this observation, combined with another series of AVB procedures (n=42) in which no strokes were observed (personal communication, John W. Brown, MD, 2008), strongly suggests that AVB surgery is brain protective in the periprocedural period. The low stroke rate associated with AVB surgery probably reflects fundamental differences between this procedure and conventional AVR. These differences include avoidance of ascending aortic cross-clamping and manipulation (cannulation, aortotomy) that are mandatory during conventional AVR and are related to stroke,\textsuperscript{30} minimization or avoidance of cardiopulmonary bypass, avoidance of debridement of the calcified stenotic valve and annulus, and absence of intracardiac air. We hypothesize that the distribution of blood flow after AVB surgery (ie, approximately one third of blood flow through the native stenotic valve and two thirds via the conduit) protects the brain from thromboembolism arising from the prosthetic valve because no blood flow to the brain is derived from the conduit. This might decrease both perioperative and long-term stroke risk after AVB surgery compared with conventional AVR.

Midterm survival after AVB was acceptable and reflected the desperately ill nature of our patient population. The outcomes of our patients compare favorably with the natural history of unoperated symptomatic AS. In 1 series, survival without surgery was 65\% at 1 year and dropped to 20\% at 2 and 3 years.\textsuperscript{31} In another series of elderly patients treated with balloon aortic valvuloplasty, survival at 1, 2, and 3 years was 55\%, 35\%, and 23\%, respectively.\textsuperscript{32} In addition, rehospitalization was necessary in the majority of patients (64\%), and functional limitation was common.

There has been a total absence of late conduit obstruction, and we have not identified any conduit valve dysfunction, with our longest survivor now 4 years out from surgery and in New York Heart Association class I. AVB is a durable operation, with reported survival after AVB exceeding 24\%\textsuperscript{33} and 25 years (personal communication, John W. Brown).

This study extends our observations of the hemodynamic and clinical results of AVB surgery in a high-risk group of patients with symptomatic AS. AVB surgery consistently and reliably relieved the hemodynamic burden of the stenotic aortic valve and can be performed without median sternotomy, cardiopulmonary bypass, and cardiac arrest. Progressive refinements of operative techniques have been associated with improved clinical outcomes. The very low rate of stroke and renal dysfunction suggests that AVB might be brain and kidney protective. We believe that AVB surgery is an important therapeutic option for the very high-risk AS patient. Continued improvements in technology and surgical technique may make this operation more accessible for the cardiac surgeon and may warrant extending AVB surgery to moderate-risk groups.

Disclosures
Dr Gammie has ownership of stock in Correx Inc and is a consultant to Medtronic Inc. The other authors report no conflicts.

References
Recent recognition that a large number of symptomatic patients with aortic stenosis (AS) are not referred for surgery as a result of real and perceived risks of conventional aortic valve replacement has sparked interest in alternative therapies. Aortic valve bypass (AVB; apicoaortic conduit) surgery relieves AS by shunting blood from the apex of the left ventricle to the ascending thoracic aorta through a valved conduit. AVB surgery has been performed, albeit uncommonly, for >45 years. The aim of this study was to characterize outcomes in a series of very high-risk AS patients treated with AVB surgery. A total of 31 patients underwent AVB surgery. In all cases, the heart was beating, and no ascending aortic manipulation was necessary. Cardiopulmonary bypass was used briefly in 61% of patients and has been used less commonly as experience has been gained in performing AVB surgery on the beating heart. Echocardiographic analyses demonstrated that AVB surgery was effective at relieving the outflow obstruction associated with valvular AS, that blood flow was predictably distributed between the conduit and native left ventricular outflow tract, and that left ventricular performance was preserved after surgery. Stroke and renal dysfunction were uncommon after AVB surgery. This experience suggests that AVB surgery is an important therapeutic option for the high-risk AS patient. Continued improvements in technology and surgical technique may warrant extending AVB surgery to moderate-risk AS patients.
Aortic Valve Bypass Surgery: Midterm Clinical Outcomes in a High-Risk Aortic Stenosis Population
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