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STATE-OF-THE-ART PAPER

Minimally-Invasive Valve Surgery

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Minimally-invasive approaches have become increasingly important in cardiac valve surgery. Smaller incisions have become commonplace in many major centers. We reviewed the existing literature and present the current state-of-the-art of minimally-invasive valve operations in this paper. (J Am Coll Cardiol 2010;56:455–62)

Minimally-invasive cardiac valve surgery represents a recent, significant paradigm shift. Traditionalists were initially resistant to such techniques, claiming smaller incisions lead to poor exposure and inferior outcomes. The rapid development and refinement of techniques over the past decade have led to the realization that a minimally-invasive approach enables complex valve surgery to be performed with results, at the very least, equivalent to those of conventional (open) valve surgery done in experienced centers. Minimally-invasive valve surgery (mini-VS) has now evolved into a safe, efficient treatment option providing greater patient satisfaction and fewer complications. All mini-VS are undertaken only after becoming skilled in performing the conventional operations.

Methods

A thorough literature search was performed using MEDLINE. Search strategy combined "mitral valve," "aortic valve," and "minimally invasive." The search was also extended to Cohn's textbook *Cardiac Surgery in the Adult* (1) and various reviews (2–8).

History

The first successful cardiac operation was performed on September 7, 1896, in Frankfurt, Germany by Rehn (9), followed by the first successful cardiac valve operation in 1912 by Tuffier (10) and the first successful mitral valve (MV) operation in 1923 (11). In 1956, Lillehei repaired multiple valvular lesions through a right thoracotomy using cardiopulmonary bypass (CPB) (12). The ensuing years witnessed the rapid development of various valvular prostheses placed via a conventional approach—a full sternotomy with CPB.

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In the 1990s, the success of laparoscopic operations in general surgery renewed an interest in minimally-invasive approaches for cardiac surgery. Navia and Cosgrove (13) and Cohn et al. (14) performed the first minimally-invasive valve operations (via the right parasternal and transsternal approaches). Remarkably, excellent exposure was achieved through smaller incisions, thereby making complex valve repair possible and safe.

In 1996, Carpentier et al. (15) performed the first video-assisted mitral valve repair (MVR) through a minithoracotomy using ventricular fibrillation. With more experience, video-assisted, 2-dimensional endoscopes and robotics were introduced by Carpentier et al. (15) and Chitwood et al. (16,17). Soon thereafter in 1998, the Leipzig group (Germany) used a 3-dimensional videoscope with voice-activated robot assistance (Aesop 3000, Computer Motion, Goleta, California), enabling solo surgery (18). Also in that same year, Carpentier et al. (19) performed the first completely robotic MVR using the Da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, California).

An important adjunct in the evolution of mini-valve surgery (mini-VS) is the parallel progress in perfusion technology. First, smaller, nonkinking arterial and venous cannulae have been combined with vacuum-assisted venous drainage to allow maximal space use provided by the smaller incisions. Second, the implantation of transjugular coronary sinus catheters provides cardiac protection via retrograde cardioplegia. Third, the application of carbon dioxide (CO_2) into the operating field limits intracardiac air (to reduce air embolism). Finally, intraoperative transesophageal echocardiography allows for real-time monitoring of cardiac distention, de-airing, and cannula placement (20).

Thus, mini-VS has evolved into a routinely performed operation with excellent results in many specialized centers (13,21–24).

Definition of Mini-VS

The Society of Thoracic Surgeons (STS) database (25) defines minimally-invasive cardiac surgery as "any procedure

Abbreviations and Acronyms

AF = atrial fibrillation

AV = aortic valve

BWH = Brigham and Women's Hospital

CPB = cardiopulmonary bypass

Mini-MVS = minimally-invasive mitral valve surgery

Mini-VS = minimally-invasive valve surgery

MV = mitral valve

MVR = mitral valve repair

STS = Society of Thoracic Surgeons

not performed with a full sternotomy and CPB support." According to Chitwood et al. (26,27), mini-VS should not be defined in terms of a specific procedure, but rather a "philosophy" that requires an operation-specific strategy. Each minimally-invasive strategy introduces alternatives for CPB cannulation (central or peripheral), aortic occlusion (endovascular or transthoracic), and cardioplegia delivery (antegrade, atrial retrograde, or transjugular retro-retrograde). At the Brigham and Women's Hospital (BWH), mini-VS does not involve a complete sternotomy but instead uses a partial sternotomy or limited thoracotomy incision.

Techniques of Mini-VS

Mini-VS refers to a constellation of surgical techniques/technologies (Table 1) that minimize surgical trauma through smaller incisions compared with a conventional sternotomy. The most common minimally-invasive approach to the aortic valve (AV) is the upper partial sternotomy, whereas with the MV, this includes a right mini-thoracotomy (28), a robotically assisted right thoracic approach (29), and a partial sternotomy (30).

By the mid-1990s, parasternal and transsternal approaches were being described by Navia and Cosgrove (13) and Cohn et al. (14). Smaller incisions lateral to the sternum were created, with or without resection of the third or fourth costal cartilage. However, their disadvantages included femoral CPB cannulation, ligation of the right internal thoracic artery, occasional chest wall instability, and difficult conversion to full sternotomy. In 1997, Cohn et al. (28) presented 84 minimally-invasive cases (41 aortic, 43 mitral) using a right parasternal incision and excising the third and fourth costal cartilage. Interestingly, greater patient satisfaction, a decrease in post-operative atrial fibrillation (AF), and overall lower costs were found (28). Later, Greelish et al. (29) primarily used a lower mini-sternotomy for mini-MVS with excellent results.

Specially designed instruments facilitate mini-VS via a thoracotomy. Chitwood et al. (16) designed a new aortic clamp that allows transthoracic aortic occlusion. Video assistance has also been used for mini-VS through small thoracotomies (17,21,22). Although there are highly encouraging results using a right thoracotomy, several disadvantages exist, including peripheral CPB cannulation, the need for a double-lumen endotracheal tube, and occasional difficulty with MV exposure (21). Another important technique is the port access for mini-MVS (30), with promising results (31–34). However, the port access technique, mainly performed by the Stanford group, continues to be associated with some risk (peripheral CPB cannulation and a high rate of retrograde aortic dissection caused by using the balloon catheter to occlude the aorta and provide cardioplegia). An 8-cm anterolateral thoracotomy via the third intercostal space, direct aortic clamping, and cannulation have been described by Angouras and Michler (35).

Telemanipulators, robotics that allow a handlike mechanism to be controlled by a human operator, were first used in Paris, France by Carpentier et al. (15) and Falk et al. (18) in Leipzig, Germany. Telemanipulator-supported operations, which involve femoral cannulation and direct or endoluminal aortic clamping, have been used and propagated by Chitwood et al. (17,23) and others (36,37), who claim that this technique could be safely and effectively used (28). Recently, another group reported the results of 25 patients receiving successful telemanipulator-supported mini-MVS (38); however, long-term results are not available. Other centers (Leipzig) had similar positive experiences using the telemanipulator-supported techniques in the late 1990s (39,40). However, they later abandoned this technique, given the lack of difference compared with their "standard" approaches. In 2009, Wang et al. (41), in Nanjing, China, presented a new approach for MV replacement through a right vertical infra-axillary thoracotomy with excellent results (0.5% mortality).

Results

During the past 15 years, cardiac surgeons worldwide have reported their mini-VS data with promising results. The

Table 1 Various Approaches/Incisions of Minimally-Invasive Valve Surgery

Thoracotomy
Right anterior thoracotomy, second and third intercostal spaces (52,78)
Right anterior thoracotomy, fourth and fifth intercostal spaces (85)
Left lateral thoracotomy (40)
Left posterior thoracotomy (51)
Right vertical infra-axillary thoracotomy (41)
Partial sternotomy
Parasternal incision (6,13,14)
Transsternal incision (6)
Upper sternotomy (7)
T mini-sternotomy (86)
Inverted T sternotomy (87)
Reversed L-shaped partial upper sternotomy (88)
Reversed L incision (89)
Inverse L incision (86)
J incision (6,90)
V incision (91)
Video-assisted
Port access (30–34)
Robot-assisted
AESOP 3000 (Computer Motion, Goleta, California) (6,18)
Da Vinci (Intuitive Surgical, Inc., Sunnyvale, California) (19)
Zeus (Computer Motion, Goleta, California) (6)

main statement is that minimally-invasive operations can provide excellent, safe, and familiar exposure of the MVs and AVs with results comparable to those with conventional approaches. However, a randomized, prospective trial comparing minimally-invasive and conventional valve operations is still lacking. We therefore must rely on retrospective (mostly single-center) clinical evaluation trials.

Mortality. After reviewing all comparative mini-VS studies evaluating mortality, no study showed a significant difference between minimally-invasive and conventional approaches (42–49).

At our institution (BWH), the mortality rate is comparable to that with conventional valve approaches. In 1997, Cohn et al. (28) reported a low mortality rate in mini-VS: 2 of 41 patients (5%) for the AV replacement/repair and 0 of 43 patients (0%) for MV. Both operative deaths were in New York Heart Association functional class IV patients; 1 died of liver failure and 1 died of an arrhythmia in a reoperation (28). In 2001, Cohn et al. (8) presented 353 mini-MVS patients over a 5-year-period. The results showed a mortality rate similar to that with conventional sternotomy, a shorter intensive care unit/hospital stay, and overall lower costs (8). Furthermore, this series found a lower number of blood transfusions, incidence of AF, and post-discharge rehabilitation requirements; patients indicated that they had a faster recovery (8). In 2003, Greelish et al. (29) reported the first long-term results (5-year follow-up) of mini-VS, indicating a freedom from mitral regurgitation and reoperation >90% of patients. In 2004, Mihaljevic et al. (3) from the BWH group showed that of 1,042 patients undergoing AV surgery, 526 operations were minimally invasive, with a mortality rate of 2% (12 of 526 patients), and in the mini-AV group, the mortality rate was 3% (14 of 516) versus conventional sternotomy. Furthermore, mini-MVS had an operative mortality rate of 0.2% (1 of 474) compared with 0.3% (1 of 337) with conventional sternotomy. The freedom from reoperation rate at 6 years was 95%, and the late mortality rate was 3% in the MV group (3).

In their early port access cases, Mohr et al. (34) reported a high mortality rate (9.8%) for mini-MVS, partially procedure related, with 2 of 51 patients experiencing an aortic dissection (34). After discontinuing the port access technique, and modification and simplification of the surgical procedure, the mortality decreased to an in-hospital mortality rate of 3.9% (4). The Leipzig long-term results revealed an actuarial survival rate of 83% at 6.8 years (50). When excluding the initial 200 patients in whom an endoclamp was used, the overall results are even more impressive (50). In 2002, Mohr's group (Onnasch et al. [45]) reported their 5-year experience performing mini-MVS in 449 patients, with a mean survival rate of 96.3% at 2-year follow-up. In 2002, Grossi et al. (51) reported their 6-year experience with mini-MVS in 714 patients, with a 1.1% hospital mortality rate for isolated MVR and 5.8% for isolated MV replacement. Morbidity included a permanent neurological deficit (2.9%) and aortic dissection (0.3%), respectively (51). They concluded that mini-MVS is reproducible with low perioperative morbidity/mortality and late outcomes comparable to those with conventional operations (51).

Casselman et al. (52) (Aalst, Belgium) reported their results with 306 patients undergoing mini-MVS in 2003. Their MVR rate was 73.9%, and the overall hospital mortality rate was 1%. In addition, post-operative morbidities included re-exploration (8.5%), new-onset AF (17%), and pacemaker implantation (2.3%). Ninety-three percent of patients stated that they would choose the same procedure again, and 46.1% were back at work within 4 weeks. They concluded that endoscopic MVS can be performed safely but definitely requires a learning curve (52). As a result, minimally-invasive approaches have become their exclusive strategy for isolated atrioventricular valve disease (52).

Soltesz and Cohn (2) reported 890 mini-AVSs (875 AV replacement, 15 AV repair) that were performed at BWH (2) with a 30-day operative mortality rate of 2% (18 of 890) lower than the risk-unadjusted mortality rate for AV replacement from the STS database (3.4% to 4.4%). Of note, 157 of 890 were performed on patients 80 years or older (mean age 84 years) with an operative mortality rate of 1.9% (3 of 157), with no mortality among 34 octogenarians who underwent a minimally-invasive reoperative AV replacement (2). Thus, this reveals exceptionally good survival for this age, suggesting that the benefits of mini-VS may be increased in higher-risk subgroups (2,3).

Cosmesis. Improved cosmesis is an undisputed benefit of mini-VS. In a study of patients having a right thoracotomy, Casselman et al. (52) reported that approximately 99% of patients thought that their scar was esthetically pleasing.

Neurological events. Due to the physical limitations of mini-VS, inadequate de-airing leading theoretically to a higher incidence of neurological complications was a primary concern, making the use transesophageal echocardiography mandatory, which had minimized air emboli and stroke in the BWH series. In their early series, Mohr et al. (34) reported an 18% incidence of post-operative confusion; however, continuous CO_2 insufflation was not used, as in more recent series. One decade later, Seeburger et al. (50) (Mohr's Leipzig group) observed post-operative neurological impairment in 41 of 1,339 patients (3.1%) who underwent mini-MVS, with 28 (2.1%) minor and 13 (1.0%) major events. Ten different studies reported no difference in the incidence of stroke (27,42–44,46,47), whereas 2 found a decreased incidence with a minimally-invasive approach (17,46). In a systemic meta-analysis (53), there was no significant difference in neurological events in 6 eligible studies including a total of 1,801 patients.

Bleeding transfusion and re-exploration. Smaller incisions should theoretically reduce post-operative bleeding and transfusion requirements, notably with the significant morbidity/mortality associated with transfusions and bleeding re-exploration (54). Some studies report no difference in transfusion requirements (55), whereas others note fewer blood product transfusions with mini-VS. However, in most case, these data are not risk adjusted (56,57). In a prospective, randomized trial, Dogan et al. (58) found a significant decrease in post-operative chest tube output in the mini-VS group compared with the conventional group. Others, for example, Grossi et al. (48) (case-control study), found that a right thoracotomy was associated with 51% fewer blood products than a conventional sternotomy. In robotically assisted MVR, transfusion requirements are even lower (20% to 45% require transfusions) (18,59).

Furthermore, 4 comparative studies found less blood loss: a mini-thoracotomy was used in 3 (17,27,32) and a parasternal approach was used in 1 (49). Chitwood et al. (17) demonstrated no difference in blood loss/blood product transfusions in 31 video-assisted MV procedures, compared with conventional sternotomy, despite fewer re-explorations for bleeding. The addition of a voice-activated robotic camera led to a decrease in blood loss as well as in CPB and cross-clamp times (27). Three of 10 studies found reduced transfusion requirements with a minimally-invasive approach compared with conventional surgery (14,47,48), whereas the others showed no difference (17,27,32,43,49,54,60). In patients 70 years or older, Grossi et al. (47) found reduced plasma transfusions with a minimally-invasive ($n = 111$) compared with a conventional ($n = 259$) approach. More convincing evidence came from a subsequent study by the same group that showed 13% fewer total transfusions with 1.8 fewer units of red blood cells using a mini-thoracotomy compared with a conventional sternotomy (48). Similar data were confirmed by Cohn et al. (14) in patients undergoing mini-MVS. Two of 7 studies (17,27) demonstrated a reduced need for reoperation for bleeding with a minimally-invasive approach (3,42–44,49). Further, 5 studies showed a significant reduction in reoperations for bleeding with a minimally-invasive approach ($n = 1,553$, $p = 0.02$) (3,42–44,49). The recent data of the Leipzig group on post-operative course included reoperation for bleeding in 69 patients (5.1%) (50).

In another study regarding AV surgery, Soltesz and Cohn (2) found that in 890 minimally-invasive AV surgeries, post-operative bleeding necessitating reoperation occurred in 2.6% (23 of 890); 50% of patients required blood transfusion (mean transfusion 1.8 U/patient).

AF. Theoretically, it has been suggested that a less traumatic surgical approach would trigger less post-operative AF. However, 5 of 6 studies demonstrated that this is not the case (17,27,32,42,43,61). A meta-analysis of 4 eligible studies revealed no significant difference between minimally-invasive and sternotomy approaches ($n = 539$, $p = 0.45$). Asher et al. (61) addressed this question in a cohort of 100 patients having elective primary minimally-invasive AV or MV surgery compared with a matched control group undergoing conventional sternotomy. They found a similar prevalence of post-operative AF using either method, even after stratifying for valve type. However, the PAIR registry reported a 10% incidence of new-onset AF with the port access technique, which is lower than that expected for sternotomy (32).

Wound infection. The incidence of wound infections and septic complications is lower with a thoracotomy than with a median sternotomy. This virtually eliminates mediastinitis (47,48), which is uncommon but possible after a partial sternotomy. Grossi et al. (48) reported an incidence of 0.9% for mini-thoracotomy and 5.7% for sternotomy cases ($p = 0.05$). This had increased to 1.8% and 7.7%, respectively, in elderly patients ($p = 0.03$) (48), whereas Felger et al. (27) reported no significant differences.

It is important to note that there is an additional risk of groin complications associated with mini-VS. Such complications are now added complications, not present with a traditional sternotomy approach.

Pain, quality of life, and recovery. Compared with a complete sternotomy, thoracotomy incisions are associated with less pain, discomfort, and post-operative analgesics (27). Port access in completely endoscopic robotic approaches may further reduce post-operative discomfort. Also, lower narcotic requirements may potentially reduce post-operative delirium (27). Within 4 weeks after a right thoracotomy, approximately one-half of the patients return to work and full activity (17).

Post-operative pain and quality of life were evaluated from 1996 to 1997 by the Leipzig group using different scoring systems (62). This group revealed less pain from the third post-operative day onward after a lateral mini-thoracotomy (vs. a standard sternotomy) (62). Better stability of the bony thorax leads to earlier mobilization and return to daily activities. Thus, patient-related factors are a significant advantage of mini-VS. In concordance with their findings, Yamada et al. (60) in 2003 compared early post-operative quality of life in mini-VS and conventional valve surgery.

Of all the potential benefits of mini-VS (e.g., improved cosmesis, less pain), faster return to normal activity is the most consistent finding. Four studies measuring post-operative pain exist, and all found a reduction of pain compared with a sternotomy (14,32,54,55); 2 studies reported a faster return to normal activities (14,32). Glower et al. (32) found that post-operative pain resolved more quickly with a minimally-invasive approach; patients returned to normal activity 5 weeks earlier than after a median sternotomy (4 ± 2 weeks vs. 9 ± 1 week, $p = 0.01$). At BWH (14), we found less pain (in-hospital and after discharge), less analgesic use, greater patient satisfaction, and return to normal activity 4.8 weeks before sternotomy patients. Mihaljevic et al. (3) noted patients undergoing minimally-invasive aortic surgery had shorter length of stay and with more frequent discharge home without additional stationary rehabilitation services. Casselman et al. (52) reported that 94% of their patients reported no or mild post-operative pain, 99.3% reported an esthetically pleasing scar, 93% would choose the same procedure again if they needed additional surgery, and 46% returned to work within 3 weeks. Perhaps the most insightful evidence comes from 2 studies reporting that patients undergoing surgery via a minimally-invasive approach as their second procedure all thought that their recovery was faster/less painful than their original sternotomy (27,63).

The use of small incisions, which necessitates, for example, rib retractors, results in less pain, given less stretching of the muscle fibers, compared with sternotomy retractors.

Hospital stay and costs. Minimally-invasive approaches appear to be associated with faster recovery, earlier discharge, and reduced use of rehabilitation facilities (13,55,58,64,65). Does a rapid recovery translate into a shorter hospital stay/reduced costs? Although cost data for mini-VS have not been thoroughly evaluated, length of hospital stay is a known surrogate for resource use and hospital costs (54). Asher et al. (61) found that patients who underwent an upper hemisternotomy had significantly less perceived pain, shorter hospital stay, and a greater proportion of home discharges than those who had conventional full sternotomies.

Eight of 14 studies reported a shorter hospital stay with a minimally-invasive approach (3,14,17,27,32,43,46–49,62). Only 5 studies were eligible for the meta-analysis of Modi et al. (53), and although the trend indicated this to be the case, the result was not statistically significant (350 patients, $p = 0.07$). Chitwood et al. (17), Cohn et al. (14), and Navia and Cosgrove (13) equated this trend to a 34%, 20%, and 7% cost saving, respectively. Moreover, these patients had fewer requirements for rehabilitation, a significant advantage in health care savings: 91% were discharged home compared with 67% with conventional approach (3,14).

Intermediate and long-term results. Mihaljevic et al. (3), from Boston, presented mini-MVS with actuarial survival rates of 98%, 97%, and 95% at 1, 3, and 5 years, respectively. Among patients undergoing conventional sternotomy, there were actuarial survival rates of 97%, 91%, and 86% at 1, 3, and 5 years, respectively ($p < 0.03$). Regarding mini-AVS, they also reported 24 of 526 (5%) late deaths in the follow-up of the minimally-invasive group for actuarial survival rates of 98%, 94%, and 82% at 1, 3, and 5 years, respectively, compared with 56 of 516 deaths (10.8%) in the conventional sternotomy group for the actuarial survival rates of 94%, 90%, and 86% at 1, 3, and 5 years, respectively ($p < 0.006$) (3).

The data presented by Seeburger et al. (50) showed the following results. The Kaplan-Meier estimate for survival at 5 years was 82.6%, and freedom from MV-related reoperation was 96.3%.

Comparing a consecutive cohort of 100 mini-thoracotomy MVSs with the previous 100 sternotomy MVSs, Grossi et al. (44) found a comparable 1-year freedom from reoperation rate (96.8% vs. 94.4%, $p = 0.38$) with similar net improvement in functional class. Mihaljevic et al. (3) reported a significantly better actuarial survival rate at 5 years for mini-MVS compared with sternotomy patients (95% vs. 86%), but this may be explained by a lower risk profile. Many of the cohort studies are temporally updated results from a few high-volume centers (Cleveland Clinic, BWH, New York University Medical Center, Leipzig). Therefore, only the most recent data from 10 cohorts with 6,479 patients are considered (2,32,51,52,66–70). The crude unadjusted mortality rates for the entire cohort are 1.1% for MVR and 4.9% for MV replacement. The corresponding data from the STS 2007 report (71) are 1.5% for MVP and 5.5% for MVR. With regard to long-term survival, there are 7 studies reporting survival rates from 100% at a mean of 2.3 years to 83% at 6.8 years post-operatively (29,33,52,66,68–70). This compares favorably with the 5-year survival rates of 86.4% reported by the Mayo Clinic (72) and 82% reported by the Cleveland Clinic (73). Five studies reported freedom-from-reoperation rates ranging from 99.3% at 3.2 years to 91% at 4 years (29,52,68–70). The longest follow-up was 6.3 years, with a 96.2% freedom-from-reoperation rate. Again, this compares favorably with the Mayo Clinic data, which indicate a risk of reoperation of between 0.5%/year for isolated posterior leaflet prolapse and 1.64%/year for isolated anterior leaflet prolapse (57).

Elderly patients. Two studies looked at minimally-invasive techniques in elderly patients (47,74). Grossi et al. (47) reviewed 111 patients undergoing mini-VS who were at least 70 years old and compared them with 259 patients undergoing a sternotomy. The minimally-invasive group had a significantly lower incidence of sepsis and wound complications, required fewer frozen plasma transfusions, and had a shorter hospital stay. The authors concluded that this approach can be used safely in operations on the elderly population with excellent results. Also, Tabata and Cohn (74) recently reported 123 cases of mini-MVR in patients aged 70 years and older with a 1.6% operative mortality rate as well as a 5-year actuarial survival rate of 87% and a 5-year freedom from reoperation rate of 93%.

As mentioned previously, at BWH, Soltesz and Cohn (2) noted that 157 minimally-invasive AV replacements were performed on patients 80 years of age or older with an operative mortality rate of 1.9% (3 of 157) with no mortality in the 34 octogenarians. This suggests that the benefits of mini-VS may be increased in higher-risk subgroups.

Mini-VS criteria. Despite the highly encouraging results from mini-VS, the criteria are both surgeon and patient dependent and on a case-by-case basis. With different training backgrounds, patient populations, and surgical approaches, surgeons should use the technique that they believe will result in the best outcome and with which they feel more comfortable. However, at the BWH, we perform mini-VS in patients with obesity and chest wall deformity and those at higher risk of sternal infections. Contraindications for mini-VS include concomitant cardiac procedures (i.e., valve + coronary artery bypass graft, multiple-valve disease).

Discussion

Cardiac valve surgery operations have historically been performed via a standard median sternotomy and CPB. With the advent of minimally-invasive surgery, several new observations regarding the treatment of patients with isolated valve disease have arisen. Patients now demand less invasive procedures with equivalent safety, efficacy, and durability. New surgical techniques should lead to smaller incisions, less blood loss, shorter hospital stays, and lower cost (74–84). Given the unprecedented increasing costs of health care, mini-VS provides a solution for savings. We are thus convinced that the future of cardiac surgery is mini-VS.

New technology and techniques must provide the same safety and quality as conventional methods. If scientific evidence shows mini-VS results in lower complication rates, surgeons *must* be trained in the newer techniques. However, with different training backgrounds, patient populations, and surgical approaches, surgeons should use the technique that they believe will result in the best outcome and with which they feel most comfortable.

In this review, we provide an overview of the exciting results of mini-VS. Several obstacles in the literature on mini-VS exist, which makes a clear definition of "minimally-invasive" difficult. The STS (71) defines minimally-invasive surgery as any procedure not performed with a full sternotomy and CPB; this definition is problematic in valve surgery.

Second, a true randomized, prospective trial comparing mini-VS and conventional VS does not exist. We must therefore rely on prospective, high-volume, and single-center clinical evaluation trials. After comparing the outcomes of the high-volume centers (BWH, East Carolina University, Cleveland Clinic, Leipzig, Aalst, New York University Medical Center, and others), there are promising data regarding mortality rates. The studies that we reviewed do not show a significant difference in overall mortality between minimally-invasive and conventional approaches. Interestingly, the different types of minimally-invasive approaches (right thoracotomy vs. partial sternotomy with J, C, T, or L type, with the exception of the port access method) do not play an important role (77,85–91). It is clear that the mortality rate is unchanged and independent of the approach used. We have also reviewed secondary factors: surgical trauma, post-operative complications, intensive care unit/hospital stay, pain, quality of life, and costs.

With mini-VS, scepticism still exists (i.e., potential "tradeoff" of smaller incisions and limited exposure). As with any new procedure, a learning curve exists that influences outcomes. Nevertheless, high-volume centers have proven that mini-VS can be performed as safely and expeditiously as conventional surgery.

One disadvantage has been the use of femoral cannulation and perfusion. In fact, groin complications (e.g., infections, arterial dissections/hematoma) account for morbidity unseen with conventional sternotomy. In addition, retrograde aortic dissections may occur; thus, the thoracic aorta is monitored for severe atherosclerotic changes by preoperative transesophageal echocardiography before using the technique. The question is: can surgeons provide the same quality without complete exposure of the heart? The answer, based on our vast experience, is an emphatic "yes!" The quality of valve surgery has been equal to that of the standard operations. We have not experienced perivalvular leaks in any of the valves implanted, and there has been excellent visualization to perform complicated MVR, including leaflet resection, chordoplasty, and commissuroplasty, documented by intraoperative and post-operative transesophageal echocardiography. Thus, we believe that the quality of operations has not been mitigated.

In several studies, the ischemia time and bypass times are somewhat longer than with the standard operation, but the length of stay and total costs were less than for standard procedures. Conversely, we learned that in high-risk patients, minimally-invasive procedures may not be as useful given the necessity for speed and efficiency to minimize ischemia and bypass times. Indeed, some of the outliers in the reviewed series were sicker patients who might benefit from limited incisional trauma, but may have lingered longer in the hospital because of slightly increased perfusion and ischemia times.

Finally, these techniques are a paradigm for the future in terms of cost-effectiveness. If the same quality of operation can be performed through a less traumatic/better cosmetic incision, resulting in a shorter hospital stay and lower overall cost, this approach would coincide with the goals of managed care. It is estimated that post-hospital care exceeds billions of dollars in the U.S.; thus, patients would have less need for rehabilitation.

Data for mini-VS after previous cardiac surgery are limited but consistently demonstrate reduced blood loss, fewer transfusions, and faster recovery compared with repeat sternotomy. Almost every patient who has undergone mini-VS after a previous sternotomy reports a less painful recovery. As for the future, mini-VS is likely to become widely adopted as patients will not opt for a sternotomy. However, despite the enthusiasm for minimally-invasive procedures, caution cannot be overemphasized because traditional cardiac operations have proven long-term success and remain our measure for comparison. Surgeons performing mini-VS should be very experienced in the standard approach and diligent in evaluating the results to ensure the highest quality of valve surgery.

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