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REVIEW ARTICLE

Minimally invasive aortic valve replacement: is the effort justified?

Sathyaki Purushotham Nambala[1] · **Arul Furtado**[1] · **Dharmesh Aggrawal**[1] · **Rashmi Nanjundaiah**[1]

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Abstract
Minimally invasive aortic valve surgery has been increasingly adopted by many as an alternative approach for aortic valve replacement over the last decade. Even so, considerable confusion continues to persist as to its benefits in terms of patient satisfaction, outcomes, cost effectiveness and other claimed advantages in comparison to the sternotomy approach. A review of published literature since the inception of the technique suggests that the minimally invasive approach for aortic valve replacement is reproducible and may eliminate the need for a full sternotomy in most patients.

Keywords Minimally invasive aortic valve replacement · Mini AVR · Upper hemi-sternotomy

Introduction

The earliest attempts at replacing the aortic valve via a minimally invasive approach (mAVR) were reported close to two decades ago. The desire for a minimally invasive approach to cardiac surgery in the 90's was spurred by the emergence of laparoscopic and less invasive forms of non-cardiac surgery. The decade saw an emergence of ideas and techniques related to minimally invasive cardiac surgery ranging from approaches and perfusion techniques to myocardial protection. The aortic valve in view of its anatomical proximity to the chest wall and therefore its accessibility made it suitable for these early attempts. However, the universal early adoption of these techniques was hampered by several limitations that isolated these developments to a few centers. Lack of appropriate instrumentation, nonavailability of suitable perfusion cannulae, lack of awareness, the fact that conventional sternotomy approaches were well established with exceptional safety profiles, excellent exposure and reproducibility, and lastly, the resistance to change from within the specialty were all factors. The last decade has seen renewed vigor in the desire to adopt less invasive approaches to aortic valve surgery. The emergence of catheter-based techniques has partly fuelled this resurgence while mounting evidence seems to suggest that the technique is safe. This article traces the evolution of mAVR to its current state.

✉ Sathyaki Purushotham Nambala
sathyaki@gmail.com

[1] Department of Cardiothoracic Surgery, Apollo Hospital, 154/11, Bannerghatta Road, Bengaluru 560076, India

Material and methods

Articles selected for this review were identified on the PUBMED database using the search terms "minimally invasive aortic valve surgery," "minimally invasive," "minithoracotomy," "right anterior thoracotomy," and "upper hemisternotomy." All published studies from the existing literature were identified until April 2017. All articles that reported using a catheter-based aortic valve replacement (AVR) or a sutureless valve were excluded from this review.

Summary

Definitions and surgical approaches

Minimally invasive cardiac surgery (MICS) is best seen as a "concept" or "philosophy" that aims to reduce the invasiveness of a cardiac surgical procedure. In achieving this, the procedure will often have to be tailored to a particular situation. The STS database defines minimally invasive cardiac surgery as "any procedure that does not involve a full sternotomy (FS) or cardiopulmonary bypass (CPB)". This definition is limiting to an extent that a catheter-based AVR and off pump minimally invasive coronary artery bypass

(MICS CABG) would practically be the only two procedures that would represent it.

AVR has traditionally been performed via a FS with central cannulation for cardiopulmonary bypass (CPB).

The earliest attempts at minimally invasive aortic valve replacement (mAVR) were by a 10 cm right parasternal incision with excision of the 3rd and 4th costal cartilages as reported by Cosgrove and Sabik at the Cleveland Clinic in 1996 [1]. Lung herniation, a major drawback, resulted in the technique being soon abandoned.

The upper hemisternotomy approach described by Cohn et al. [2] in 1997 in a series of 20 cases soon gained popularity. In this technique, a 5–7 cm midline skin incision is made beginning at the sternal notch and extending down to the 3rd or 4th intercostal space. An oscillating saw is then used to split the sternum from the sternal notch down to the chosen interspace. The sternal incision is then angled into the 3rd or 4th right interspace. Several modifications of the hemisternotomy have been described. The "j" sternotomy is an upper hemisternotomy as described earlier [3, 4]. The "J" or reversed "C" sternotomy aims to preserve the manubrium and therefore begins as a transverse sternal incision in the right first intercostal space immediately above the 2nd rib [5]. The upper hemisternotomy can also extend into bilateral interspaces at its lower end, what has been termed inverted "T" sternotomy [6]. This approach while providing better exposure is associated with a higher risk of sternal instability. The "I" sternotomy is similar and extends into bilateral interspaces at both the upper and lower ends of a limited sternotomy [7]. The familiarity of the exposure provided by an upper hemisternotomy and the ease with which it can be converted to a FS makes it the most frequently used approach for a mAVR.

In recent years the right anterior mini thoracotomy (rmAVR) approach has gained wider acceptance. The earliest attempts at AVR by a right anterior thoracotomy approach were reported by Rao and Kumar [8] in 1993, whereas Benetti et al. [9] in 1997 described approaching the aortic valve from the third intercostal space by a small right anterior mini thoracotomy. In this approach, a 5 to 7 cm incision is made over the 2nd intercostal space beginning at the right sternal border. The third costal cartilage may or may not be divided depending on the exposure required. Similarly, the right internal mammary artery does not require to be sacrificed but often is, particularly if the costal cartilage is cut. This approach while offering adequate exposure lacks the familiarity of a midline approach and may not be suitable in all patients. It is more demanding and several technical considerations need to be addressed—in particular the position of the aorta. A preoperative computed tomography (CT) scan should show that more than 50% of the aorta is to the right of the right border of the sternum. Other anatomical considerations include the distance of the aorta from the sternum and the inclination of the aorta in relation to the midline [10]. The various approaches are illustrated in Fig. 1.

Several other aspects of the mAVR operation need discussion. Arterial cannulation can either be central or peripheral and the choice depends on the approach and access. The upper hemisternotomy approach allows easy access to the distal ascending aorta and central aortic cannulation is feasible in all. Venous cannulation can also be central (right atrial) which is familiar but most prefer percutaneous femoral venous cannulation, as this reduces clutter and aids better exposure. Central cannulation in the right anterior minithoracotomy approach can be technically more difficult. The choice depends on the extent of access to the ascending aorta, with most preferring peripheral cannulation of the femoral artery and vein in the groin. Peripheral cannulation does carry the risks associated with retrograde perfusion like embolisation and dissection; some centers routinely perform imaging studies of the pelvic and groin vessels to assess diameter and the extent of atherosclerotic burden while others have done away with it relying on a Seldinger technique with transesophageal (TEE) echo guidance.

Aortic cross clamping can be done directly through the main incision in both approaches, but is less convenient in the right anterior thoracotomy approach. Clamping can also be done using a Chitwood® clamp (Scanlan International, Inc., St Paul, MN, USA) inserted from a site remote from the main incision further improving visibility. Cardioplegia for myocardial protection can be either antegrade, retrograde, or a combination of both. A retrograde cardioplegia cannula can be placed either directly through the incision or percutaneously via the right internal jugular vein with positioning in the coronary sinus guided by TEE. Single-dose cardioplegia can be beneficial as repeat dosing through a small incision can be cumbersome. A left ventricular vent if needed can be placed directly into the right superior pulmonary vein or percutaneously into the pulmonary artery.

The technique of aortotomy and valve replacement remains the same as in conventional surgery. The use of single-shaft instruments designed for minimal access cardiac surgery can further aid exposure and placement of sutures.

Routine use of TEE accords an additional level of safety in the placement of cannulae, deairing the heart and detailed intraoperative assessments as well.

Results

In the past two decades, several studies have been published on the outcomes of mAVR, with a few comparing outcomes with the traditional sternotomy approach [11]. The first decade can be seen as an evolutionary phase where many modifications were made to the conduct of the operation. This translated to several changes in approach, cannulation techniques,

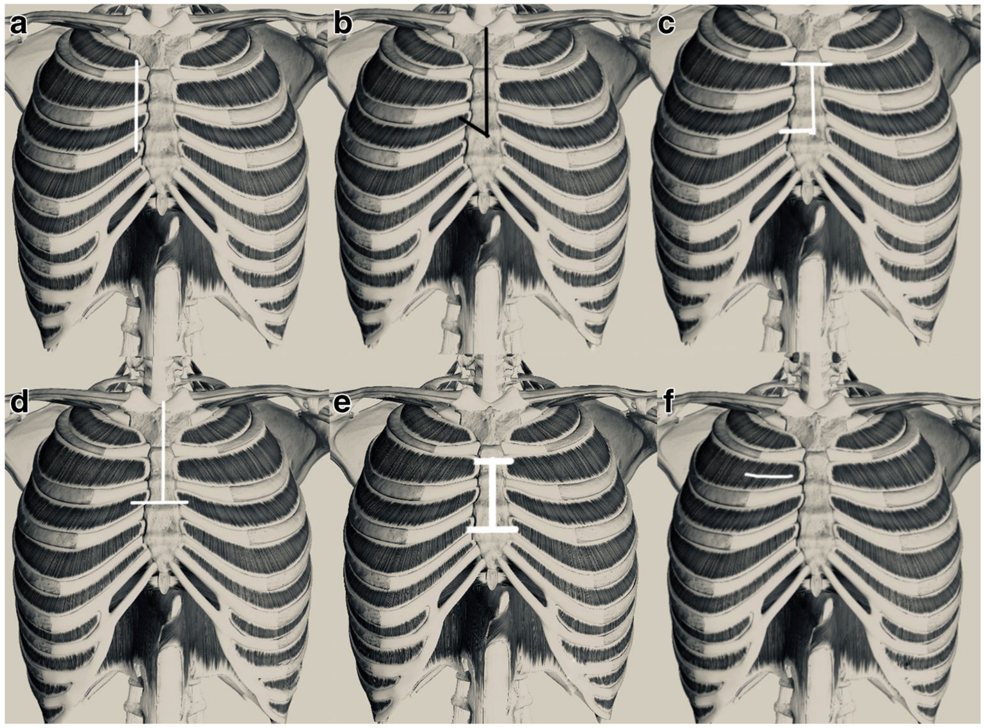

Fig. 1 Types of incisions for minimally invasive aortic valve replacement. **a** Right parasternal incision. **b** Upper hemisternotomy. **c** "J" or reverse C approach. **d** Inverted "T" approach. **e** The "I" approach with transverse sternotomy at either ends. **f** Right minithoracotomy

and strategies for myocardial protection. This coupled with the availability of specialized cannulae for establishing peripheral cardiopulmonary bypass, cardioplegia delivery, and single-shafted instruments enhanced reproducibility.

Although the procedure has been in vogue for more than 2 decades, large prospective randomized trials are lacking. Among the available trials, several shortcomings need to be taken note of. The majority of published studies compare the upper hemisternotomy technique, the outcomes of which may differ from the right anterior thoracotomy approach. The prospective randomized trials currently available have a small number of patients [11–17] and often the procedures are performed by different surgeons, which can be a confounding factor. These randomized trials are listed in Table 1. Some of the observational studies are limited to specific population subgroups such as octogenarians [18, 19], reoperations [19, 20] or left ventricular dysfunction [21] and are limited to specific institutions [19, 21]; the outcomes of which may be difficult to generalize. Propensity score-matched studies attempt to simulate the randomization of subjects as occurs in randomized controlled trials (RCT) but unlike RCT's the balancing achieved by propensity scoring is only on identified confounders rather than all possible confounders. These studies therefore are not reliable and cannot account for patient risk

Table 1 Minimally invasive AVR randomized controlled trials

Author	Year	No of patients	Approach	Findings	Statistically significant variable
Aris [11]	1999	40	Reversed L(13) UMS; reversed J(7)	Increased cross clamp time in mAVR. Better cosmesis	–
Machler [12]	1999	120	L shaped UMS	Decreased ventilation time, reduced chest drainage and pain	Ventilation time, Blood loss Analgesia usage
Bonacchi [15]	2002	40	UMS reversed L reversed C	Reduced blood loss, transfusion, shorter ventilation time with mAVR	Respiratory function better
Calderon [16]	2009	77	Reversed	No improvement of respiratory function by smaller incision	Reduced intraoperative blood loss with no reduction in transfusion
Dogan [13]	2003	40	UMS	Longer CPB time. No difference in pain or respiratory function	Chest tube drainage
Ahangar [17]	2013	60	Right anterolateral thoracotomy	Decreased pain, infection and length of stay	Average pain score Length of incision

UMS upper mini sternotomy, *mAVR* minimally invasive aortic valve replacement, *CPB* cardiopulmonary bypass factors that are not included in the scoring model. The outcome of the published data is summarized below.

The few randomized studies published have small cohorts and compare partial sternotomy to the FS technique [11–16]. While all established the safety and reliability of the approach, only one [13] showed significantly reduced blood loss. Similarly, operative time including cardiopulmonary bypass (CPB) and cross clamp times were longer in all studies. In the only matched trial comparing sternotomy and PORT ACCESS using the right mini-thoracotomy approach, Brinkman et al. [22] demonstrated shorter intensive care unit (ICU) and ventilation time, shorter hospital stay but longer operating and CPB time. Interestingly, this study demonstrated that flattening of the learning curve operative and CPB time were similar to open cases but cross clamp time remained significantly longer.

Several large observational trials clearly establish that mAVR can be performed with no additional risk of death or other major adverse events [22–40]. Cross clamp and perfusion time were longer in all except one [40], although none showed any adverse effects as a result of this. Statistically significant differences in chest tube output and hospital stay were found in favor of mAVR in this study [40]. The larger propensity score matched trials comparing mAVR with a FS also establish that there are no differences in mortality or other major complications such as stroke, renal failure, pneumonia, or re-exploration for bleeding [26–33]. The outcomes in relation to blood transfusion, postoperative respiratory function, hospital stay, and long-term survival are somewhat controversial and often contradictory. Cross clamp and CPB time was found to be similar in both approaches in most [41, 42] except in two trials. While one [24] demonstrated statistically significant reduction in both CPB and cross clamp time, the other [43] demonstrated a significant increase; this last study also reported statistically *significant increase in survival* at 5 and 8 years in patients who underwent mAVR. No specific reason could be attributed to this increase in survival. Others have reported this as well [30, 44] although no statistical significance was found. This study [43] also found more re-explorations and blood transfusion requirements in the mAVR group while there were no differences in hospital stay or duration of ventilation. All other studies showed better lung function or shorter ventilation, reduced ICD drainage and need for blood transfusion, and hospital stay. Renal dysfunction was found to be less in one study [41] while another showed a significant increase in renal dysfunction [27]. The larger observational studies and their outcomes are listed in Table 2. One small observational study [48] comparing port access AVR to FS AVR showed significant reduction in blood usage, ventilation time, ICU, and hospital length of stay while CPB; cross clamp times were significantly prolonged.

Two large meta-analysis have been conducted so far. Brown et al. [45] in their meta-analysis of 4586 patients with 2054 in the upper partial sternotomy group showed mAVR to be safe with no difference in early mortality. Shorter hospital and ICU stay, shorter ventilation time, and less blood loss within 24 h were noted in the mAVR group. There were no differences in rates of atrial fibrillation, stroke, and sternal complications. CPB and cross clamp times were longer although no adverse effects could be demonstrated. In another meta-analysis of 4667 patients, Murtuza et al. [49] found no significant differences between the two groups for CVA, renal failure and respiratory failure. Ventilation time and hospital and ICU stay were found to be shorter as with the previous study. Similarly, CPB, cross clamp, and operative time was found to be longer. No clear advantages could be demonstrated in relation to postoperative pain, its impact on respiratory function both immediate and late, quality of life, and cost effectiveness. While meta-analyses have the power to improve the power of small inconclusive reports, they cannot improve the quality of the study and inherent limitations exist.

Studies comparing the rmAVR with sternotomy are more limited and are listed in Table 3. Two of the larger observational studies, one of which was propensity matched showed no difference in outcome [31, 51]. Both studies showed longer CPB, cross clamp, and overall operative time. No other benefits were noted. One study [30] showed reduced incidence of atrial fibrillation, blood transfusion, shorter mechanical ventilation time, and postoperative length of stay. Two studies compared mini-thoracotomy to the mini-sternotomy approach with contradictory outcomes. Miceli et al. [52] demonstrated that mini-thoracotomy was associated with better outcomes, while Semsroth et al. [27] reported poor postoperative outcomes including longer CPB and cross clamp times and conversion to sternotomy with the mini-thoracotomy approach. In a more recent propensity score matched study of 492 patients, Bowdish et al. [53] reported less intraoperative blood usage, shorter ICU, and hospital stays while CPB time, cross clamp time, and other adverse events remained similar between the two groups.

Conversion

Conversion to FS seems to vary widely from none to 13% [52]. Tabata et al. [54] reported an incidence of 2.6% in a large series of 907 patients undergoing mAVR over a period of 9.5 years with a mortality of 33% in the converted group. Conversion appears to be higher with rmAVR but one study comparing mAVR by a hemisternotomy to rmAVR showed no difference [52]; the other [27] showed 13% conversion rate with a mortality of 14%. This higher mortality could be attributed to the difficulty of converting a mini-thoracotomy to sternotomy.

Table 2 Large observational studies comparing partial sternotomy to full sternotomy

Author	Year	Study type	No of Pts	Approach	Major findings	Statistically significant variable
Johnston [24]	2012	Propensity matched	1193 (832)	J sternotomy	Resource utilization decreased, shorter cross clamp time	Less drainage, transfusion, better lung function, lower pain, shorter stay
Furukawa [42]	2014	Propensity matched	808 (404)	Upper hemisternotomy	No difference	None
Tabata [19]	2007	Retrospective	1005	Upper hemisternotomy	Lower infection rates, better outcomes in elderly	
Brown [45]	2009	Meta-analysis	2054	Upper hemisternotomy	Longer CPB/ X clamp, reduced ventilation/blood loss	Shorter hospital and ICU stay
Machler [12]	1999	Prospective, observational	60	Upper hemisternotomy	Less pericardial effusion	Less ventilation, blood loss
Bakir [40]	2006	Retrospective	232	J sternotomy	Shorter ventilation, ICU and hospital stay	Shorter CPB, X clamp, Chest tube output, Hospital Stay
Murtuza [49]	2008	Meta-analysis	2249	Upper hemisternotomy	Longer CPB/ X clamp	Less transfusion, Shorter ventilation, ICU/hospital stay
Ghanta [46]	2015	Multicenter	442	Upper hemisternotomy	Decreased ventilation, blood usage, hospital stay and total cost.	Hospital stay and cost
Doll [35]	2002	Prospective, observational	176	Upper hemisternotomy	Faster recovery	Lower blood loss, shorter ICU/hospital stay, improved survival
Neely [47]	2015	Propensity matched	552	Upper hemisternotomy	Similar transfusion, shorter ventilation	Shorter CPB/X clamp time, ICU/Hospital stay
Merk [43]	2015	Propensity matched	479	Upper Hemisternotomy	Longer CPB/ X clamp, higher re-exploration rate	Increased survival
Shehada [41]	2015	Propensity matched	585	Upper hemisternotomy	Longer CPB/ X clamp time, lower respiratory and renal insufficiency	Lower respiratory and renal insufficiency, less ventilation and transfusion

Table 3 Studies on AVR through right minithoracotomy

Author	Year published	No of patients	Study type	Significant findings
Sharony [32]	2004	438 (233)	Propensity matched	
Plass [50]	2009	165	Observational	Reduced complication rate
Glower [51]	2010	306	Observational	Reduced blood loss and transfusion
Ruttman [31]	2010	87	Prospective propensity matched	Significantly longer CPB, Clamp time, Higher renal insufficiency,
Brinkman [22]	2010	90	Observational	Shorter ventilation and hospital stay
Glauber [30]	2013	192 (138)	Propensity matched	Lower incidence of AF, Shorter hospital stay
Gilmanov [18]	2013	182	Propensity matched	Reduced ventilation time, blood transfusion and incidence of AF

AF atrial fibrillation, *CPB* cardiopulmonary bypass

Re-exploration and transfusions

Several studies report blood loss and blood transfusion to be lower in the minimally invasive group [13, 30, 33, 40, 43–45, 49, 51, 52]. Byrne et al. reported less blood loss with HS than FS for redo cardiac surgery (10 vs 47%) [55]. One study contradictorily demonstrated a significantly lower red blood transfusion and re-exploration rate in the FS group [43].

Transfusion protocols vary between surgeons and institutions; none of the studies highlight their transfusion practice making it difficult to draw an inference. Similarly, re-explorations vary, depending on the threshold of surgical teams. In the study by Shehada et al., blood loss and transfusion rates were similar but re-exploration rates were higher in the mAVR group although not statistically significant [41]. Re-exploration for bleeding varied from 0 to as high as 13% [27] and a statistically significant increase with mAVR was found in one study [43].

Ventilation time, ICU, and hospital length of stay

Minimally invasive cardiac procedures have less chest wall disruption; this should theoretically translate to less pain, better postoperative lung function, and therefore impact ventilation time as well as ICU and hospital length of stay. The few randomized trials with their small cohorts show no clear benefit. Several propensity-matched trials however do demonstrate a significant advantage [30, 41] (Table 2). Neely and colleagues [47] compared 552 matched pairs and found HS patients had less time on the ventilator and shorter ICU and hospital stay compared to Ghanta et al. [46] in a multicentre trial analyzing 1341 patients across 17 centers reported similar benefits in favor of mAVR (rmAVR or HS).

Murtuza et al. [49] in their meta-analysis of 2249 also demonstrated a statistically significant advantage in favor of mAVR. Similar findings were noted in patients with previous cardiac surgery and in octogenarians [18, 56]. Miceli et al. [52] reported shorter ICU and Hospital LOS with 251 rmAVR patients comparing with 155 HS.

Infection

An important benefit of a less invasive approach is the decreased incidence of surgical site infection, sternal dehiscence, and the need for refixing the sternum but these complications appear comparable. The rmAVR approach eliminates sternal complications but has a similar incidence of groin cannulation site infection or seromas [27]. An additional advantage of less sternal disruption is its effect on postoperative pneumonia; however, there is little data to corroborate.

Neurological events

Stroke rates between mAVR and FS appear to be similar [30, 35]. Theoretically with peripheral cannulation, retrograde perfusion, the difficulty of deairing and longer CPB/ cross clamp time, the incidence of stroke or other minor neurological events would be expected to be higher with mAVR. One study [43] showed a higher incidence of delirium with mAVR while cerebrovascular accidents were higher in the FS group.

Pain

Pain is an important factor impacting several aspects of immediate postoperative recovery. Multiple studies report pain scores but scoring systems vary and the pain management strategy is not standardized. Randomized show no difference in pain between FS and HS. Johnston et al. [24] in their propensity-matched study of 832 patients demonstrated statistically significant reduction in pain. Brown et al. [45] in their meta-analysis showed a small difference in pain scores in favor of HS (1.7 lower score on a scale of 0–10). Several authors report reduction in pain based on analgesic usage early after surgery [2, 12] or faster mobilization (assumed to be because of less pain) [35, 40]. Ahangar and colleagues assessed pain scores using a numerical rating scale at 24, 48, and 72 h. Significant reduction in pain was noted with rmAVR vs FS AVR [17].

Quality of life

There is little data looking at quality of life after mAVR. Walther et al. [57] used the Nottingham Health Questionnaire to assess quality of life before and after surgery. They compared HS vs FS and found that the quality of life decreased for all patients initially as was to be expected with major surgery; it improved at 3 months irrespective of surgical choice. They also reported early ambulation can be achieved with rmAVR due to a stable chest in addition to psychological advantage accorded by the less invasive nature of the procedure.

One study demonstrated superiority of upper hemisternotomy AVR over FS AVR in terms of return to normal activity and work. They also observed "feel like myself"was experienced at 6.3 weeks for minimal access AVR compared to 10.3 weeks for FS AVR [1].

Redo surgery

Studies have compared the outcomes for AVR in a redo setting in patients who have undergone previous cardiac surgery by a median sternotomy. Pineda et al. [56] published their outcomes comparing patients undergoing redo AVR using rmAVR vs conventional sternotomy. The redo rmAVR patients were older with a higher incidence of patent grafts from a previous CABG with comparable STS scores. There were no mortalities, with shorter ICU and hospital stay for those who underwent rmAVR. Kaneko et al. made similar observations comparing reoperative AVRs in octogenarians [20]. While mortality was similar, the mAVR group showed a survival benefit at 1 and 5 years of follow-up.

Cost

Studies evaluating the costs associated with mAVR are few. Ghanta et al. [46] showed 5% reduction in total hospital costs in patients who underwent mAVR. This difference was largely attributed to earlier discharge and less blood product usage. Cohn et al. [2] and Cosgrove and colleagues [1] have shown similar reduction in total hospital costs amounting to $7000 and 19%, respectively.

Future perspective

Minimally invasive aortic valve replacement whether it is via hemisternotomy or right minithoracotomy is a safe procedure with outcomes comparable to full sternotomy based on current available evidence. While selected groups have demonstrated superior outcomes particularly with respect to blood transfusion, duration of hospitalization, lung function and pain, the evidence is inconsistent and therefore not compelling. A shorter period of recuperation and return to productive life, the impact on quality of life, and possibly life expectancy are the benefits that most would assume to be associated with a less invasive procedure. This evidence however is simply lacking. Large randomized trials with compelling outcomes are needed to establish mAVR as a valid alternative in most patients. This would not only make it a strong contender to emerging trans catheter valve therapies but also enthuse more surgeons to adopt as an alternative. At present, the adoption of trans catheter valve therapy appears to be progressively increasing in both Europe and North America. In the developing world, cost is a major determinant in the choice of therapy and trans catheter valve therapy is expensive and out of reach for most patients requiring an AVR. The emergence of favorable evidence for mAVR could establish it as a strong and viable alternative that would truly justify the effort.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This is a review article and all information has been retrieved from articles already published or in press. No human participants were involved in the study.

Informed consent Not applicable as no individual participants were included in the study. The article is a review article.

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