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Advancements in less-invasive aortic root, ascending aorta and arch surgery: current evidence and future directions

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Summary

Aortic surgery is one of the most challenging areas in cardiovascular medicine because of the complexity of the procedure and the potential for life-threatening complications. Historically, median sternotomy has been the gold-standard approach for thoracic aortic interventions, providing excellent exposure to the entire ascending aorta and the distal aortic arch. This approach has yielded satisfactory postoperative results over the years. However, the invasiveness of median sternotomy is associated with significant surgical trauma, increased postoperative pain and prolonged recovery. Minimally invasive aortic surgery has emerged as a potential alternative to conventional approaches with the aim of combining the benefits of minimally invasive cardiac surgery with the demands of complex aortic interventions. In this review, we aimed to critically analyse the current experiences with minimally invasive aortic surgery via partial upper sternotomy for the treatment of aortic root, ascending aorta and aortic arch pathologies. The partial upper sternotomy (PUS), as a less invasive approach in minimally invasive aortic surgery, represents a substantial advancement in the field of aortic surgery. The current literature on minimally invasive aortic surgery via PUS is predominantly based on retrospective, single-centre studies with small sample sizes, which limits the strength of the conclusions and generalisability. Ventilation time, intensive care unit (ICU) stay, length of hospital stay and bleeding complications can be reduced using this approach. Survival was not negatively affected and cosmetic results were improved by minimally invasive aortic surgery.

Introduction

Aortic surgery is one of the most challenging areas in cardiovascular medicine because of the complexity of the procedure and the potential for life-threatening complications. Historically, median sternotomy has been the gold standard approach for aortic interventions, including ascending, root and arch interventions, providing excellent exposure to the entire ascending aorta and the distal aortic arch. This approach has yielded satisfactory postoperative results over the years [1–3]. However, the invasiveness of median sternotomy is associated with significant surgical trauma, increased postoperative pain and prolonged recovery.

In recent years, there has been a paradigm shift towards less-invasive surgery, also referred to as minimally invasive cardiac surgery (MICS), driven by the desire to reduce surgical morbidity and enhance patient recovery [4–6]. The advantages of minimally invasive cardiac surgery extend beyond improved cosmetic outcomes; they include reduced surgical trauma, decreased blood loss, shorter hospitalisation and less painful postoperative courses [7–9]. These benefits have contributed to faster patient recovery and higher patient satisfaction. Telyuk et al. were able to show that there was no difference in all-cause mortality, reoperation rates, echocardiography data and major adverse cardiac events in their aortic valve patient cohort during a six-year follow-up. Considering this, non-inferiority of minimally invasive cardiac surgery is promising for further advancements in this field [10, 11]. Recently, a meta-analysis of more than 17,000 patients comparing different minimally invasive cardiac surgery approaches with median sternotomy suggested that mortality rates among median sternotomy and minimally invasive cardiac surgery are comparable [12, 13]; however there was a tendency towards fewer respiratory and renal insufficiencies, as well as shorter hospital and intensive care unit (ICU) stay [14].

Despite the identified disadvantages associated with minimally invasive cardiac surgery, including reduced exposure of the operative field, extended operation times corresponding to the learning curve, the necessity for specialised surgical instruments and the intraoperative conversion rates to conventional surgical techniques, minimally invasive cardiac surgery continues to be a compelling area of inquiry within the field of cardiac surgery [13, 15, 16]. The growing acceptance and accumulation of expertise in minimally invasive cardiac surgery has raised the question of its applicability in more-complex cardiac procedures, such as aortic surgery. Less-invasive aortic surgery has emerged as a potential alternative to conventional approaches with the aim of combining the benefits of minimally invasive cardiac surgery with the demands

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of complex aortic interventions [17, 18]. Minimally invasive aortic surgery (MIAS) offers the prospect of accelerated patient recovery without compromising the surgical outcomes.

The standard approach for minimally invasive cardiac surgery in aortic valve surgery is partial upper sternotomy (PUS), which may also provide adequate exposure for various minimally invasive aortic surgery procedures while minimising surgical trauma [19]. The partial upper sternotomy technique was first described by Cohn et al. using a "J" incision [20], and later by Svensson with an "L" incision [21]. These approaches have been refined over the years and shown to be feasible for various aortic pathologies.

Despite the potential advantages of minimally invasive aortic surgery via partial upper sternotomy, its adoption has been gradual, primarily due to concerns about surgical exposure, technical challenges and the steep learning curve associated with minimally invasive techniques [22, 23]. Moreover, the majority of studies on minimally invasive aortic surgery have been retrospective and single-centre, limiting the generalisability of their findings [24]. As a result, there is a need for comprehensive evaluations of minimally invasive aortic surgery to address these limitations and provide evidence-based assessments of its efficacy and safety.

In this review, we aimed to critically analyse the current experiences with minimally invasive aortic surgery via partial upper sternotomy for the treatment of aortic root, ascending aorta and aortic arch pathologies. We will discuss the intraoperative and postoperative outcomes, compare them with conventional median sternotomy approaches and address the challenges and limitations identified in the recent literature. By incorporating recent studies and meta-analyses, we sought to provide a balanced perspective on the role of minimally invasive aortic surgery in contemporary aortic surgery.

Our goal was to highlight the potential of minimally invasive aortic surgery to improve patient outcomes. Considering that the outcomes of the indexed procedures are comparable to those achieved with median sternotomy, it is noteworthy that even open aortic arch procedures can be safely conducted with partial upper sternotomy in well-selected patients; nevertheless we would like to acknowledge the need for further high-quality research. We will also consider the impact of the surgical learning curve, importance of surgeon experience and necessity for standardised protocols and training programmes. Through this comprehensive review, we hope to contribute to the evolving discussion on minimally invasive approaches in aortic surgery and encourage wider acceptance and implementation of minimally invasive aortic surgery, where appropriate.

Pathologies

Aortic root and ascending aorta

Recent advancements in aortic root surgery have led to the exploration of minimally invasive techniques including the partial upper sternotomy approach. Elghannam et al. conducted a study on patients undergoing full root replacement or valve-sparing root replacement via partial upper sternotomy, without a comparison group [5]. Their findings revealed reoperation rates and mortality during follow-up comparable to those reported in patients undergoing median sternotomy [13, 14]. Notably, 67% of the patients reported improved quality of life and 93% expressed satisfaction with cosmetic results [12]. However, the absence of a control group and the retrospective design limit the ability to attribute these outcomes solely to the surgical approach. In a more recent study, the same group was able to corroborate previous findings, with similar operation times between partial upper sternotomy and median sternotomy. Moreover, patients with partial upper sternotomy showed less postoperative bleeding and lower pneumonia rates [4].

Shah et al. compared patients who underwent the Bentall procedure using partial upper sternotomy and median sternotomy [6]. Ventilation times in the partial upper sternotomy group were significantly shorter (5.5 h vs 17 h, $p < 0.001$), as were re-explorations for bleeding. These data regarding bleeding complications align with the available literature on the benefits of minimally invasive cardiac surgery [9]. However, the potential selection bias and retrospective nature of the study limit the generalisability of these findings.

Research conducted by our group corroborated the feasibility and safety of partial upper sternotomy for aortic root surgery [7]. Our study did not reveal any differences in cardiopulmonary bypass (CPB) and circulatory arrest between partial upper sternotomy and median sternotomy patients. We demonstrated only a reduced cross-clamp time, which may potentially improve with the learning curve and yield beneficial outcomes for patients.

A systematic review and meta-analysis by Harky et al. compared minimally invasive and conventional aortic root replacement [11]. They found that minimally invasive aortic surgery was associated with reduced operative times, less postoperative pain and shorter hospital stay. However, they emphasised the heterogeneity among studies and the need for high-quality randomised controlled trials (RCTs) to provide stronger evidence.

A recent meta-analysis compared partial upper sternotomy and median sternotomy, concluding that there was no significant benefit with respect to infections, bleeding and operation times. While these results do not align with findings from smaller studies, they suggest a trend towards reduced postoperative hospital stays and fewer intraoperative blood transfusions [25]. Furthermore, Shrestha et al. conducted a comparative study of patients undergoing the valve-sparing David procedure via either median sternotomy or partial upper sternotomy, revealing comparable early postoperative outcomes between the two surgical techniques [26]. Additionally, recent reports have emerged regarding the Endo-Bentall procedure, which is specifically reserved for a select group of patients deemed inoperable. This procedure necessitates meticulous planning, and further case studies are required to validate its efficacy [27].

The ascending aorta has emerged as a significant focal point in the realm of minimally invasive aortic surgery. Numerous studies have substantiated the feasibility and safety of minimally invasive aortic surgery for surgical interventions pertaining to this vital anatomical segment. In

the majority of instances, the ascending aorta is resected during the aortic root procedure.

Svensson et al. published their experience with ascending aorta and proximal arch surgery using partial upper sternotomy, demonstrating feasibility and acceptable outcomes [21]. The stroke and 30-day survival rates were 2% and 98%, respectively. Similarly, Tabata et al. reported a 9-year experience with minimally invasive aortic surgery via partial upper sternotomy, finding no significant differences in operative times compared to median sternotomy but observing reduced postoperative pain and shorter hospital stays with minimally invasive aortic surgery [28].

In a large propensity score-matched analysis of 8533 patients, Roselli et al. evaluated the outcomes of proximal aortic operations performed via partial upper sternotomy versus median sternotomy, obtaining 483 matched pairs [29]. Even though the study spanned over 19 years, during which time surgical techniques and perioperative care evolved, potentially confounding the results, the outcomes reached have nevertheless been extraordinary, as the in-hospital mortality in the partial upper sternotomy group was 0%, and the postoperative hospital stay (5.2 vs 6 days, $p < 0.001$) and ICU stay (24 vs 26 h, $p < 0.001$) were significantly shorter in the partial upper sternotomy group.

Rayner et al. conducted a systematic review and meta-analysis comparing aortic root and ascending aortic repair using minimally invasive cardiac surgery and median sternotomy [30]. Partial upper sternotomy was used in all but one of the 12 studies in their analysis. They found that minimally invasive aortic surgery was associated with reduced blood transfusion requirements and shorter ICU and hospital stay. However, they highlighted limitations due to heterogeneity among studies and the predominance of retrospective designs.

Aortic arch

Minimally invasive approaches for aortic arch procedures have been implemented by only a few experienced pioneers in this specialised area. Our group has published our experience with minimally invasive aortic arch repair via partial upper sternotomy, demonstrating that minimally invasive aortic surgery can be performed safely with acceptable early- and mid-term outcomes [17, 18]. In our cohort of 123 patients, conversion from partial upper sternotomy to full sternotomy was not required. Reoperation for bleeding was low, comparable to that in other reports of minimally invasive aortic surgery [31–33] and could be performed through the same incision. We did not observe any wound dehiscence, aligning with contemporary publications reporting low rates of wound complications after minimally invasive aortic surgery [34, 35].

The ICU and hospital stays in our series were comparable or at a lower range compared to other reports, including minimally invasive [31–33] or conventional [32, 36] approaches. The observed neurological morbidity is at a lower range than that of aortic series performed through a conventional [37–39] or minimally invasive [30, 33] approach. It is appealing that the minimally invasive approach does not appear to have affected cerebral protection, and thus would not be expected to result in a higher incidence of neurological injury.

El-Sayed Ahmad et al. reported their experience employing the frozen elephant trunk technique through partial upper sternotomy in a small cohort with 14 patients [33]. They observed no intraoperative conversions to full sternotomy, no reoperations for bleeding, and no spinal cord injuries or permanent neurological deficits. While these results are promising, the small sample size and lack of long-term follow-up limit the conclusions.

Aortic arch in Stanford type A aortic dissection

Surgery for aortic dissection, particularly Stanford type A, involves complex procedures to repair the damaged aorta and restore the blood flow in the true lumen. Traditionally, these surgeries have been performed through full sternotomy, which provides extensive access but is associated with significant trauma and prolonged recovery.

Wu et al. conducted a single-centre study evaluating 36 propensity-score matched patients per group undergoing surgery on the ascending aorta, including the aortic arch, for Stanford type A aortic dissection [40]. They retrospectively compared their data to those of a propensity score-matched cohort undergoing the same procedure via median sternotomy. Ventilation time (22 h vs 44 h, $p = 0.014$), ICU stay (4.6 days vs 7.9 days, $p = 0.005$) and length of hospital stay (8.2 days vs 21.4 days, $p = 0.001$) were significantly shorter in the partial upper sternotomy group. However, the drainage volume was significantly lower in the partial upper sternotomy group, but subxiphoidal drainage for late bleeding was also necessary in this group. These findings suggest the potential benefits of minimally invasive aortic surgery in acute dissections; however, the retrospective design and potential for selection bias should be considered.

Moreover, Liu et al. compared patients with Stanford type A aortic dissection undergoing hybrid total arch replacement via ministernotomy (partial upper sternotomy) versus total arch replacement with a frozen elephant trunk via median sternotomy with almost 100 patients per group [32]. Bypass times were lower in the partial upper sternotomy group, which might be due to the hybrid approach. The lengths of ICU stay (129 h vs 153 h, $p = 0.037$) and postoperative hospital stay (20 days vs 24 days, $p = 0.002$) were significantly lower in the partial upper sternotomy group. In the Kaplan-Meier survival analysis, no differences were found between the groups. The reported in-hospital mortality of 5.1% and one-year survival of 89.6% align with the available literature [18, 36].

Advancements and learning curve

Since the introduction of partial upper sternotomy in valve surgery [20, 21], advancements in the past decade have been significant. Although partial upper sternotomy has gained popularity for aortic valve surgery, further minimally invasive options have been explored [41, 42]. Experienced aortic surgeons have extended minimally invasive aortic surgery to more complex procedures, including the ascending aorta and aortic arch [6, 18, 29, 33]. These operations can be performed with non-inferior outcomes by highly trained surgeons.

The available literature suggests that ICU stay, length of hospital stay and postoperative bleeding can be reduced using minimally invasive aortic surgery [6, 29, 33, 43]. How-

ever, most studies did not notice significant differences in bypass times between groups [6, 7, 29, 33, 43]. In the large propensity score-matched analysis by Roselli et al., patients undergoing minimally invasive aortic surgery via partial upper sternotomy had a shorter bypass time (70 min vs 87 min, p = 0.001) and a shorter aortic cross-clamp time (55 min vs 70 min, p = 0.001) [3]. Since the cohort in their study was large and conducted over a period of 19 years, the results might be influenced by the surgeon's experience and learning curve.

The reported improvement in quality of life and cosmetic satisfaction among patients undergoing minimally invasive aortic surgery via partial upper sternotomy should not be underestimated [4]. These promising results demonstrate not only the safety and feasibility of minimally invasive aortic surgery via partial upper sternotomy, but also represent a milestone for future developments in this field. The advancements in partial upper sternotomy for valve surgery over the past decade have been substantial, with its application expanding beyond aortic valve procedures to more-complex operations involving the ascending aorta and aortic arch [6, 18, 29, 33]. This evolution of minimally invasive aortic surgery techniques has been driven by experienced surgeons seeking to improve patient outcomes. The available literature suggests that minimally invasive aortic surgery via partial upper sternotomy can lead to improvement of some "soft outcomes" like reduced ICU stay, shorter hospital stay and decreased postoperative bleeding [15, 19, 24, 34, 35]. Although most studies have not found significant differences in bypass times between minimally invasive aortic surgery and conventional approaches [6, 29, 33, 43], a large propensity score-matched analysis by Roselli et al. reported shorter bypass and aortic cross-clamp times for minimally invasive aortic surgery via partial upper sternotomy [29].

The benefits of minimally invasive aortic surgery via partial upper sternotomy extend beyond non-inferior or superior clinical outcomes, including improved quality of life and cosmetic satisfaction [5]. These promising results not only demonstrate the safety and feasibility of the technique but also pave the way for future developments in minimally invasive cardiac surgery. As surgeons continue to refine their skills and overcome the learning curve associated with minimally invasive aortic surgery, the advantages of this approach will likely become more pronounced.

Centre volume must be considered in the evaluation of surgical outcomes, as evidenced by Mori et al.'s assessment of over 1000 centres across the United States. Their findings indicate a significant reduction in mortality rates when the centre volume surpassed 20 to 25 non-emergent procedures annually via minimally invasive surgery [44]. Furthermore, an analysis of patients undergoing surgery for proximal aortic conditions, including aortic dissections, revealed that larger hospitals generally achieved superior outcomes. However, within the subgroup of type A aortic dissection patients, no discernible advantage was noted, possibly attributable to the requirement for highly specialised surgeons and established aortic protocols [45]. It is essential to address this aspect, as both cardiac and vascular surgery literature suggest that structured training programmes incorporating simulation can enhance individual surgeon proficiency [46, 47].

Considering the centre volume, the surgeon's expertise and the associated learning curve, we conclude that the efficacy of minimally invasive aortic surgery utilising partial upper sternotomy in complex aortic procedures is dependent on these factors. We propose that further advancements in minimally invasive surgical techniques could lead to expanded applications in cardiac surgery, thereby potentially benefiting a more diverse patient population.

Limitations and future directions

The current literature on minimally invasive aortic surgery via partial upper sternotomy is predominantly based on retrospective, single-centre studies with small sample sizes, which limits the strength of the conclusions and generalisability. Well-designed prospective studies and RCTs are needed to provide high-quality evidence on the efficacy and safety of minimally invasive aortic surgery. Recent case reports suggest that the Endo-Bentall Procedure holds significant promise in advancing the field of cardiac surgery, potentially paving the way for new therapeutic avenues and strategies [27, 48]. Furthermore, it is imperative to address the contraindications associated with minimally invasive aortic surgery. Patients undergoing reoperative surgeries, those with known arch abnormalities or individuals presenting with significantly unfavourable anatomical conditions – such as obesity or deformities of the chest wall – are generally not suited for minimally invasive aortic surgery.

Surgical interventions on the aortic arch are inherently more complex than those performed on the aortic root or the ascending aorta. This review intentionally excludes discussions on perfusion and cooling techniques and the specifics concerning circulatory arrest durations. Such factors should be considered when interpreting the literature presented.

The influence of the surgical learning curve on clinical outcomes is particularly pronounced in intricate procedures, such as aortic arch surgery performed through minimally invasive approaches. To enhance the competency of surgical practitioners and ensure patient safety, it is essential to implement specialised training programmes and comprehensive guidelines aimed at standardising techniques. These measures not only facilitate the effective integration of advanced procedures into surgical practice but also promote a culture of continuous learning and improvement among clinicians.

Conclusion

The partial upper sternotomy, as a less invasive approach in minimally invasive aortic surgery, represents a substantial advancement in the field of aortic surgery. However, to avoid jeopardising patient safety, minimally invasive aortic surgery should be performed by experienced surgeons. Nevertheless, minimally invasive aortic surgery can be taught during surgical training to promote wider acceptance. A critical evaluation of long-term patient outcomes remains essential as we implement these techniques. While minimally invasive approaches show promise, their adoption should be guided by evidence-based benefits in recovery times, complication rates and quality of life measures rather than technical innovation alone.

In this review, we emphasise the intra- and post-operative advantages. Ventilation time, ICU stay, length of hospital stay and bleeding complications can be reduced using this approach. Survival and in-hospital morbidity were not negatively affected, and cosmetic results were improved by minimally invasive aortic surgery. Since there are no long-term data on the durability of results with aortic surgery via partial upper sternotomy, careful patient selection is necessary.

Potential competing interests

All authors have completed and submitted the International Committee of Medical Journal Editors form for disclosure of potential conflicts of interest. No potential conflict of interest related to the content of this manuscript was disclosed.

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