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Surgical Technique

How We Perform Right Anterior Minimally Invasive Approach for Aortic Valve Replacement

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Abstract

Minimally invasive aortic valve replacement using an anterior right thoracotomy approach is becoming an established alternative to mini-sternotomy. This strategy offers reduced postoperative bleeding, shorter hospital stays, and fewer complications than conventional techniques. Proper patient selection is critical, especially during the initial learning curve, and includes factors such as age, risk score, obesity, and smoking status. The key advantages of this approach include smaller incisions and reduced tissue trauma, while challenges center on complex cannulation, clamp positioning, and deairing. Experience with imaging selection, appropriate incision planning, and cannulation techniques helps streamline workflow and mitigate complications. An anterior right thoracotomy for aortic valve replacement is both safe and efficient, offering comparable outcomes to traditional methods with notable advantages in patient recovery. This methodological paper can be a resource for surgeons to establish or refine a minimally invasive cardiac surgical program.

Keywords

minimally invasive; aortic valve replacement; right anterior thoracotomy; patient selection; imaging; recovery

Introduction

In the spectrum of minimally invasive cardiac surgery (MICS), the anterior right thoracotomy (ART) approach for aortic valve replacement is currently emerging as a valid alternative to mini-sterotomy [1]. Despite the lack of randomized evidence on this topic, several observational studies and meta-analyses [2] have confirmed the clinical benefit of ART in terms of reduced postoperative bleeding, length of stay in hospital, complication rates, and even procedure-related costs [3–5]. The learning curve for the procedure includes around 50 cases [6,7]. A recent consensus statement has provided technical recommendations and several governance considerations to implement before initiating an ART program [8]. This paper describes our approach to ART minimally invasive aortic valve replacement, detailing technical steps, practical considerations, and pitfalls.

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Patient Selection and Preoperative Imaging Interpretation

Patient selection has been widely discussed in the literature; meanwhile, the most recent consensus statement recommended avoiding high-risk (Euroscore >5%) patients, aged >75 years, who were classified as obese, and current smokers at the beginning of the learning curve [8].

In our practice, we have progressively widened these indications to medically complex patients, including diabetes and chronic renal disease. To mitigate the difficulties associated with morbid obesity and assess feasibility, we implemented computed tomography (CT) scan protocols with three-dimensional (3D) reconstruction and 3D printing to evaluate anatomical configuration and plan surgical access (Fig. 1 and Video 1). Such a dedicated imaging protocol has progressively expanded the indications for minimally invasive access and is currently applied to mitral surgery at our Institution. While we advocate for collaboration with the radiology department in the preoperative phase, if this approach is not available, we recommend obtaining a contrast CT scan with protocols similar to those routinely used in the preprocedural planning of transcatheter aortic valve replacement (TAVR), but with arms down (rather than the standard arms up) because of the change in the height of the intercostal space related to the aortic valve position.

Several different CT scan measures have been proposed, including the inclination of the aorta and other

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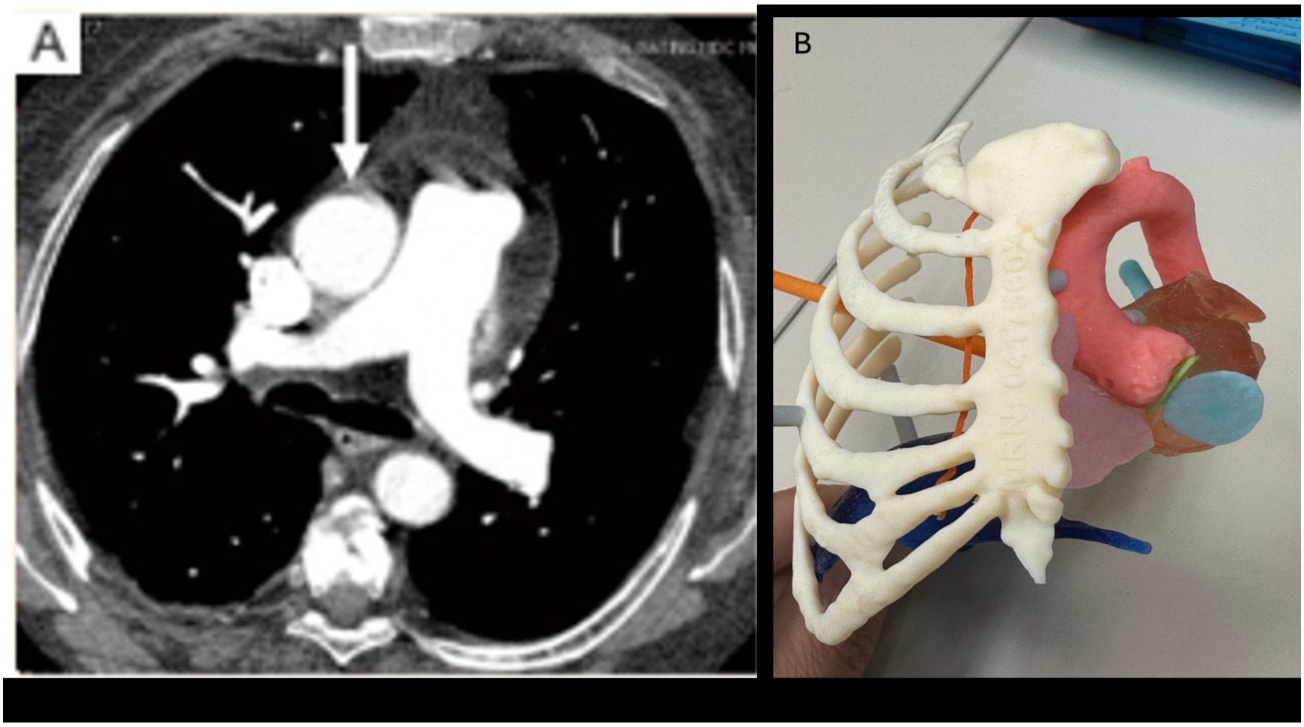


Fig. 1. Important preoperative imaging and measurements. Important preoperative surgical measurements: (A) A line is drawn from the right sternal border to the anterior aspect of the ascending aorta in the axial view using a multiplanar algorithm. It is important to assess the position of the aorta regarding the midline. The aorta should lie for the full circumference or at least more than 50% on the right side for a mini-thoracotomy approach. A CT scan should be performed "arms down" instead of the standard "arms up" to reproduce the anatomical relationship encountered on the surgical table. The arrow indicates the position of the aorta in respect to the sternum. (B) Three-dimensional (3D) printing of patient-specific thoracic anatomy shows spatial relationships between the chest and the valvular planes and allows surgical access planning. CT, computed tomography.

anatomical relations between the chest wall and aortic annulus. Ultimately, we use a two steps approach adjusted from the Van Praet approach [9], which includes first drawing a line from the right sternal border to the anterior aspect of the ascending aorta in the axial views using the multiplanar algorithm (Fig. 1A). If a direct vision approach is preferred the distance measured along this line should not exceed 10 cm; however, if a videoendoscopic approach is planned, then longer working distances are possible.

The next step is to evaluate the aortic position according to the Van Praet classification [9]. Types IA and IB, i.e., when the whole ascending aorta or more than 50% of the ascending aorta is on the right side of the line, can be addressed with direct vision ART. A left-sided ascending aorta might require a video-assisted approach.

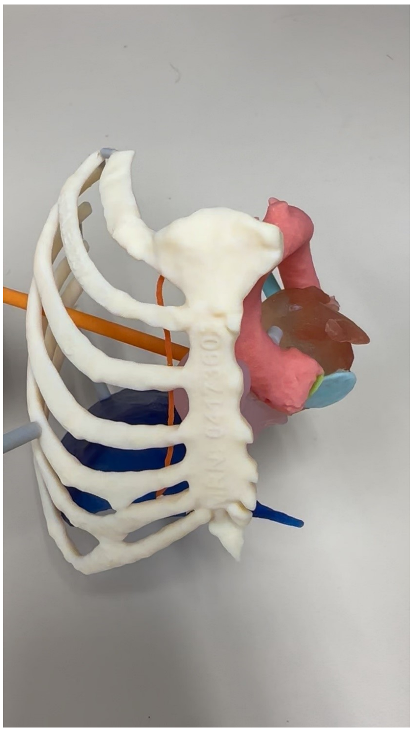
Evaluating the position of the right atrial appendage is important to select the appropriate intercostal space to provide access. The space closest to the tip of the right appendage should be selected for access.

The assessment of calcium burden on the valve is an important part of the analysis, as it could provide useful information to predict the difficulty in removing the valve and performing decalcification, particularly for bicuspid valves.

Depending on the surgical access, central cannulation might not be feasible, requiring peripheral cannulation and possibly retroperfusion. In our practice, we utilize peripheral cannulation to provide more room for aortic manipulation and clamping. We carefully assess the calibers, anatomies, and courses of the femoral and subclavian vessels—a diameter above 9 mm is considered safe for cannulation. An interposition graft can also be used in cases of smaller caliber or if there are concerns of distal perfusion. Meanwhile, in cases where the femoral anatomy is hostile or in cases of severe peripheral vascular disease, we opt for axillary cannulation with an interposition graft.

Patient Positioning and Anesthetic Considerations

The patient is supine, and a pressure bag is underneath the back at the level of the interscapular line. This will be further inflated to provide hyperextension and a right elevation of roughly 30 degrees. This maneuver would assist in pushing the aortic valve anteriorly and increase the intercostal space [10]. We recommend using either a single-lumen or double-lumen endotracheal tube (ET) or bronchial blocker. Single lumen ET tube requires being cardiopulmonary bypass since the pericardiotomy to avoid intraperi-



Video 1. Three-dimensional printing patient-specific reconstruction. We use an *ad hoc* CTA protocol with 3D printing to reconstruct patient-specific chest anatomy and assess the spatial relationship between the chest and the valvular planes. This approach is useful in the preoperative phase to establish the feasibility of the approach and plan access or port positioning. As shown in the video, we also reproduce the anatomy of the aorto–mitral curtain and the relationship between the two planes, especially when a combination of aortic and mitral surgery is planned. CTA, computed tomographic angiography. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

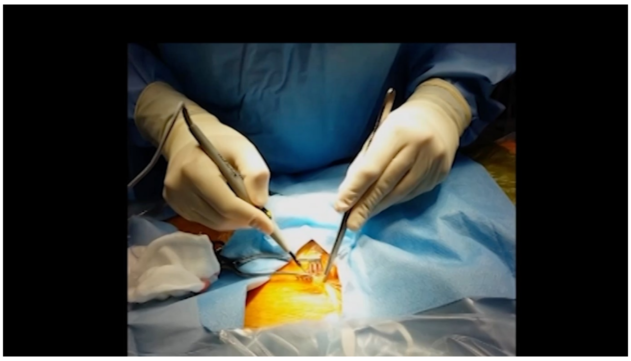
cardial injury. Defibrillator pads are placed before prepping. We suggest setting up pacing wires in an accessible position before incision to rapidly pace the heart after cross-clamp removal to avoid significant regurgitation and left ventricle distension. Transesophageal echocardiography (TEE) guides several steps of the procedure.

Cannulation and Establishment of Cardiopulmonary Bypass

The cannulation strategy includes a central and peripheral approach. Central cannulation can be achieved via the distal ascending aorta and the right atrial appendage. Alternative peripheral antegrade perfusion can be performed via the right axillary artery. Table 1 describes the available cannulation options and relative considerations for each strategy.

Usually, peripheral cannulation is achieved through the femoral vessels. Those can be accessed using the percutaneous Seldinger technique and Perclose devices or through a small cut-down.

Access for femoral cannulation is marked preoperatively and situated two finger-breadths below the imaginary inguinal ligament line between the anterior superior iliac spine and ipsilateral pubic tubercle. Cardiopulmonary bypass (CPB) is normally established after the chest incision and aortic exposure. The femoral cannulation sequence is outlined in Video 2.



Video 2. Femoral cannulation sequence. A 3–4 cm horizontal incision is made to access the femoral fascia, avoiding lymphatic vessels, followed by a horizontal incision to expose the femoral vessels beneath the inguinal ligament. If the CFA bifurcation is high, we use two 0-Ethibond sutures to suspend the inguinal ligament superiorly, improving exposure for cannulation of the common femoral artery. Limited medial and lateral dissection of the artery allows partial clamping if necessary, and full heparinization is administered. For venous access, a diamond-shaped purse-string suture with 5-0 Prolene or a simple U-stitch is used, while arterial access is achieved using a 5-0 Prolene purse string. In smaller arteries, we use a double CV-4 Goretex pledgeted suture placed parallel to the femoral axis, as this is thought to reduce the risk of stenosis when securing hemostasis at decannulation. Cannulation of both vessels follows the Seldinger technique under TEE guidance. The venous guidewire is advanced to the SVC, with care to avoid coiling in the RA, misplacement into the RV, or entry into the hepatic vein. If challenges arise, we use a stiffer guidewire (e.g., SuperStiff or Lunderquist) or a 6 Fr pigtail catheter to help guide it into the IVC. The arterial guidewire is advanced to the aortic arch, and in cases of severe tortuosity, a hydrophilic 0.035 Glidewire may be used, exchanged over a 6 Fr pigtail catheter for a standard PTFE 0.035 wire once positioned. Sequential dilators facilitate cannula insertion, and the CPB circuits are connected after careful deairing. CPB, cardiopulmonary bypass; TEE, transesophageal echocardiography; RV, right ventricle; CFA, Common femoral artery; SVC, superior vena cava; RA, right atrium; IVC, inferior vena cava. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

Table 1. Cannulation strategy options and considerations.

Type of cannulation	Indications	Contraindications	Considerations
Central	- Aorta position type IA - Unsuitable femoral anatomy - BMI <23	- Arch or ascending calcifications - Aortic position types 1B, 2, and 3	- Theoretically less risk of stroke or postoperative neurological complications (delirium, etc.) - Overcrowding of surgical field
Peripheral femoral direct	- Most cases with common femoral artery caliber >9 mm	- Significant peripheral vascular disease - Previous vascular surgery or other percutaneous access - Significant tortuosity or hostile anatomy - Calibers <7 mm (relative)	- Reported theoretical increased risk of neurological events related to retrograde perfusion (low level of evidence) - Consider Goretex parallel purse-string in case of a small femoral vessel
Peripheral femoral with interposition graft	- Small caliber femoral (<8 mm) - Concerns for distal perfusion	- Previous vascular surgery	- Increased time - Potential bleeding after heparinization
Axillary cannulation	- Hostile aortic anatomy with calcification - Nonviable femoral access	- Previous vascular access - Extremely small caliber axillary artery <5 mm	- Provides antegrade flow - Time-consuming

BMI, body mass index.

We use vacuum-assisted venous drainage (VAVD), especially if peripheral cannulation is chosen because the venous cannula is too small (ranging from 22 to 25 Fr) to provide an efficient gravity-assisted venous drainage.

Vacuum assistance should not exceed –60 mmHg to avoid erythrocyte damage [11]. The body temperature is lowered to 32 °C, and goal-directed perfusion using DO_2-guided perfusion is applied if the pump flow is reduced to 80% of the predicted flow.

Incision and Exposure

A 4–5 cm incision at the second or third intercostal space is performed for direct vision surgery. If a completely endoscopic approach is chosen, this can be reduced to 2 to 3 cm. As previously suggested, it is preferable to make the incision just above the third intercostal space and further dissect the subcutaneous tissue, so that a change in access to either the second or third is possible if needed, according to the position of the aorta (Video 3) [10].

Video 3. Landmarking for incision. For direct vision surgery, a 4–5 cm incision is made at the second or third intercostal space, while a completely endoscopic approach allows for a smaller 2–3 cm incision. It is preferable to place the incision just above the third intercostal space, enabling dissection of the subcutaneous tissue to allow flexibility in accessing the second or third intercostal space, if needed, depending on the position of the aorta. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

The right internal mammary artery (RIMA) can be sacrificed to improve the exposure of the aorta and the sterno–chondral articulation of the second or third ribs. The latter will be reapproximated using a heavy Ethibond or Polydioxanone (PDS) stitch at the end of surgery. These maneuvers will increase the invasiveness of the procedure. Meanwhile, if a totally endoscopic approach is not performed, a soft tissue retractor is inserted along with a Thoratrak™ spreader (Medtronic, Inc Minneapolis, MS, USA).

If an endoscopic approach is preferred, rib section/mobilization and RIMA sacrifice are unnecessary, and a soft tissue retractor is solely used. In this setting, a 30-degree high-resolution thoracoscope is placed through a 5 mm miniport in the same intercostal space as the working port, just a few cm laterally. This incision will be used to flood the surgical field with CO_2 (2 L/min). Thoracoscope use has significantly improved visualization of the valve components and the right coronary ostium [12–14]. The thoracoscope is a light source in direct vision or video-assisted settings [9].

A second 5 mm miniport access is achieved in the fourth intercostal space, where the left ventricular vent line is placed. The phrenic nerve is then identified, and the pericardium is opened 3 cm above the nerve superiorly to the right appendage. This is considered a safer point to incise the pericardium without damaging the heart structures. The pericardiotomy is then extended cranially towards the aortic pericardial reflection. Stay sutures are placed and passed outside the chest using a crochet hook or through the 5 mm miniports. Applying tension on the sutures laterally facilitates exposure of both the aorta and the right superior pulmonary vein (RSPV) and improves aortic traction towards the incision.

Cardiopulmonary Bypass Establishment, Venting, and Cross-Clamping

We perform a degree of dissection of the aorta from the surrounding connective tissue to prepare for the subsequent aortic clamp insertion.

CPB is established, and a pledgeted purse string for cardioplegia is placed in the ascending aorta. A long antegrade cardioplegia cannula is inserted. We use Ethibond stitches for the cardioplegia purse-string, so a Cor-Knot (LSI Solutions, New York, USA) automated system can safely secure hemostasis at the moment of the cardioplegia cannula removal. An Left ventricle (LV) vent is then placed. This vent is brought out to a port incision on the fourth or fifth intercostal space of the anterior axillary line via the guidance of a nasogastric tube to facilitate the passage and avoid crowding of the field. The LV vent sequence is outlined in Fig. 2 and Video 4.

The application of the aortic cross-clamp is outlined in Video 5. Antegrade cardioplegia is delivered into the aortic root. Additionally, the cardioplegia strategy depends on surgeon preferences. We suggest antegrade intracellular

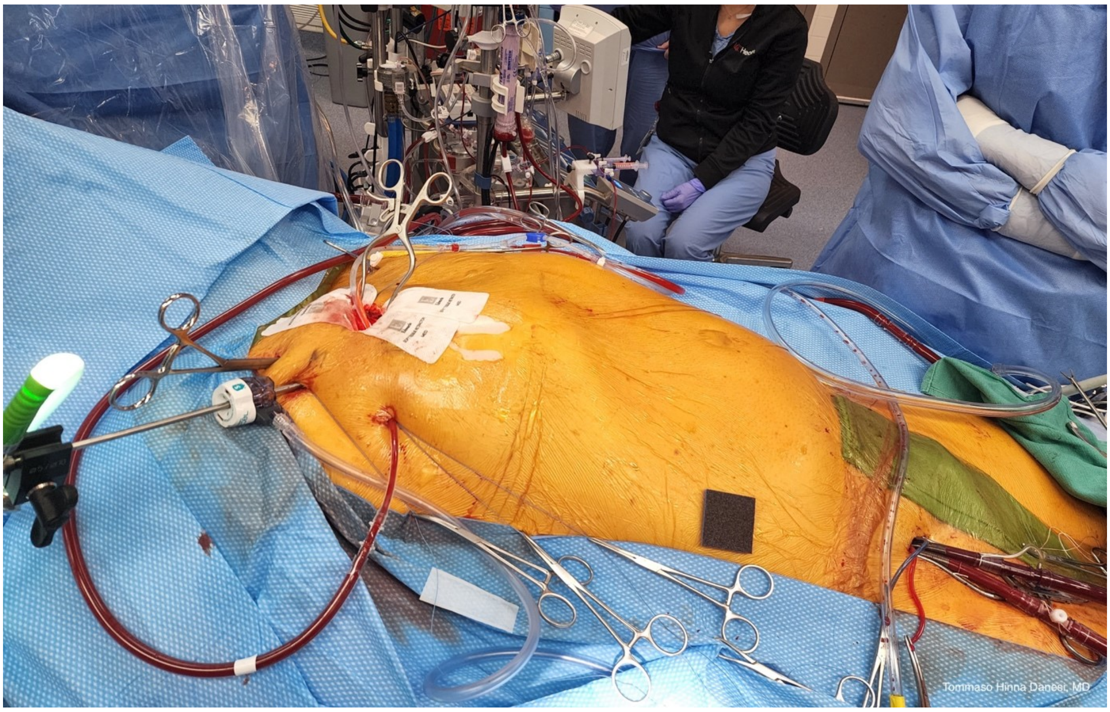
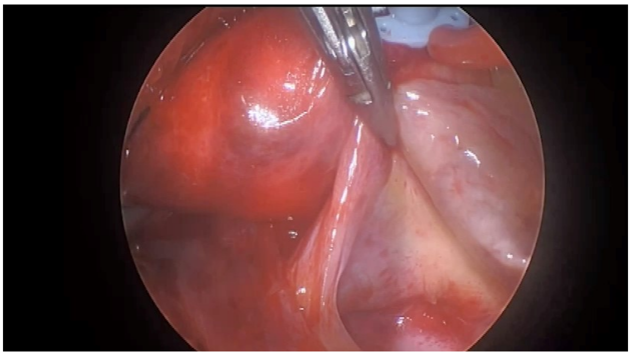


Fig. 2. Left ventricular vent and femoral cardiopulmonary bypass. Patient setup to allow for visualization of femoral cardiopulmonary bypass, a retraction port, a surgical port for the operation, and a left ventricular vent port.



Video 4. Left ventricular vent placement. A quadrangular purse-string suture is placed on the right superior pulmonary vein (RSPV), and a 16 Fr J vent is inserted into the left ventricle via the RSPV. This step can also be performed immediately after cross-clamping to reduce the risk of gaseous embolism. The left ventricular vent is then positioned and guided through a port incision at the fourth or fifth intercostal space along the anterior axillary line, using a nasogastric tube to facilitate passage and prevent crowding in the surgical field. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

crystalloid cardioplegia providing up to 2 or 3 hours of safe cardioplegic arrest without redosing, especially at the beginning of the experience. This can be changed for hematic 4:1 or 1:4 since ischemic time improves with experience. Cardioplegia delivery can be successfully achieved either in antegrade via ascending aorta or directly into the coronary ostia (especially in the presence of moderate aortic regurgitation) or retrograde via the coronary sinus (CS). Notably, specific neckline devices for percutaneous CS cannulation are available on the market; however, these devices require a certain grade of expertise from the anesthesia team and must be placed before the patient is prepped for surgery.

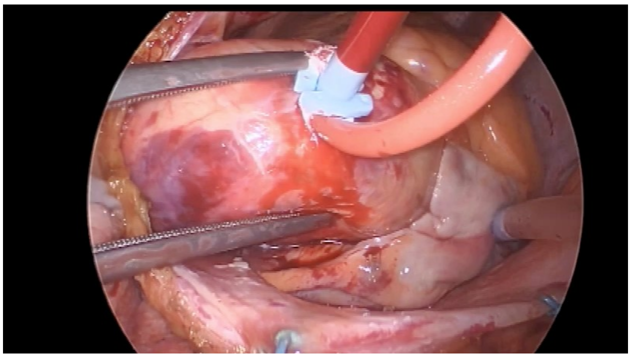
Aortic Valve Exposure, Valvectomy, and Implantation of Valve Prosthesis

We tailor the position and shape of the aortotomy according to the prosthetic valve choice. We use a high transverse aortotomy at the fat pad, or at least 3.5 cm from the valve plane, in case of a sutureless valve.

A J-stick- or italic S-shaped incision extending below the sinotubular junction into the non-coronary sinus might be necessary for rapid deployment valves, considering the size of the prosthesis skirt.

In any case, we strongly recommend avoiding extending the aortotomy medially towards the pulmonary artery because managing bleeding from this edge could be difficult and might need a second pump run.

We find using three stitches at the highest point of the aortic commissures useful to assist in retracting the aortic wall and preventing the thoracoscope from obstructing the view. Retraction of the edge of the midpoint of the aortotomy towards the head further enhances visualization [15]. In addition, inserting retraction stitches at the nadir of each valve commissure significantly enhances exposure (Video 6) [10].



Video 5. Placement of the aortic cross-clamp. Depending on the length of the ascending aorta, posterior dissection from the right pulmonary artery branch may be necessary to achieve effective cross-clamping. The Chitwood clamp, commonly used for anterior right thoracotomy (ART) aortic valve replacement (AVR), is inserted through the second or first intercostal space along the anterior or mid-axillary line. Blunt dissection is recommended to avoid pulmonary arterial damage, guiding the bottom jaw of the clamp through the upper part of the transverse sinus. The aorta can be temporarily and gently grasped with a partial clamp and pulled toward the right to ensure proper positioning between the Chitwood clamp jaws. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

Valve resection and calcium debridement are performed per routine, along with extensive irrigation with cold saline (Video 7).

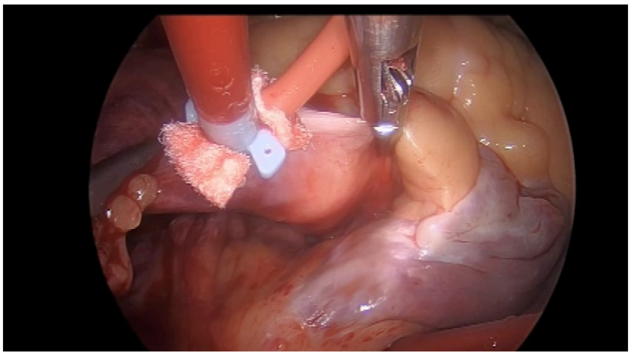
We prefer to start annular stitching on the right coronary sinus as it is the most challenging area. Mounting the needle on long-shafted instruments in a “fish-hook” fashion facilitates engagement of the annulus and stitch positioning. Each suture can be tractioned to assist the insertion of the following stitch. Different auto-annular suturing devices with pre-mounted pledget braided sutures are available; however, the experience with these devices is limited.

As previously described, when using sutureless valves in a totally endoscopic fashion, particular care should be provided to assess stitching and valve seating on the right coronary sinus, as this part is difficult to visualize with the thoracoscope [10].

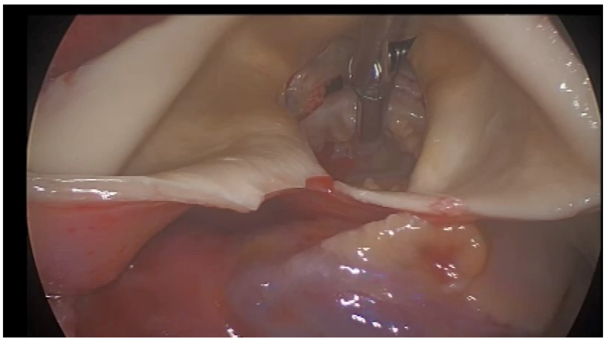
After passing sutures in the prosthesis, using automated tying devices, such as the Cor-Knot System (LSI Solutions, New York, USA), is strongly advised to assist with valve anchoring, as supported by the most recent literature (Video 8) [15–17].

Aortic Closure, Dearing, Wound Closure

Aortic closure can be performed using 4-0 or 5-0 Prolene sutures according to the preference of the surgeon. In our experience, a two-layer mattress and running suture technique represent a valid strategy to avoid bleeding (Video 9).



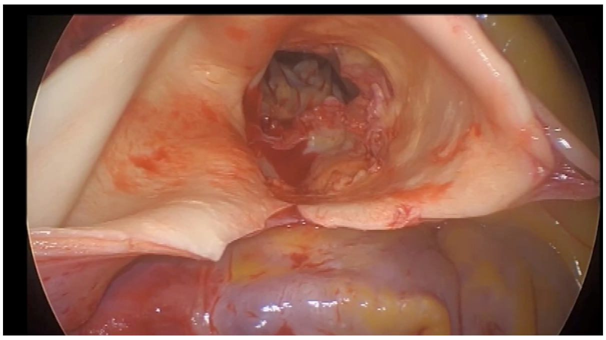
Video 6. Aortotomy. The placement of the aortotomy depends on the prosthetic valve choice. A high transverse aortotomy at the fat pad or at least 3.5 cm from the valve plane is preferable for sutureless valves. Considering the prosthesis skirt size, a J-shaped or italic S-shaped incision extending below the sinotubular junction into the non-coronary sinus may be necessary for rapid deployment valves. Avoid extending the aortotomy medially toward the pulmonary artery to prevent challenging bleeding management, which might require a second pump run. As described, placing three stitches at the highest points of the aortic commissures helps retract the aortic wall and keeps the thoracoscope from obstructing the view. Additionally, retracting the midpoint of the aortotomy toward the head and inserting retraction stitches at the nadir of each valve commissure significantly improves visualization. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.



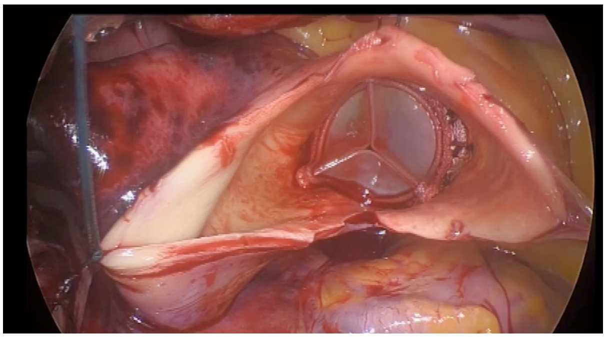
Video 7. Valvectomy and debridement. Valve resection and calcium debridement are performed per routine, along with extensive irrigation with cold saline. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

We suggest placing the epicardial pacing wire before removing the aortic cross-clamp, as accessing the free wall of the RV or its diaphragmatic aspect will be easier. The wires are passed via the initial incision used for the RSPV vent insertion.

Deairing maneuvers with the gentle filling of the LV can commence at the end of the first suture layer and continue afterward under TEE assessment, both via the aor-



Video 8. Annular stitches. Annular stitching begins at the right coronary sinus, the most challenging area. Mounting the needle on long-shafted instruments in a "fish-hook" orientation facilitates engagement of the annulus and proper stitch positioning. Traction on each suture aids the placement of subsequent stitches. Various auto-annular suturing devices with pre-mounted pledgeted braided sutures are available. When using sutureless valves in a fully endoscopic approach, special attention is needed for stitching and valve seating in the right coronary sinus, as it is difficult to visualize with the thoracoscope. After threading the sutures through the prosthesis, automated tying devices, such as the Cor-Knot System (LSI Solutions, New York, USA), are highly recommended for valve anchoring, as supported by recent literature. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.



Video 9. Aortic closure. Aortic closure is performed using 4-0 or 5-0 Prolene sutures according to the surgeon's preference. A two-layer technique combining a mattress and running sutures is recommended to minimize the risk of bleeding. Video associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8423.

tic root and the RSPV vent. Warm blood root infusion ("hot shot") before cross-clamp removal might not be ideal when using sutureless devices, as it might precipitate prosthesis migration. Similarly, excessive root manipulation in these circumstances is also not recommended. The heart is weaned from CPB as per routine and decannulated. TEE is required to assess valve positioning, function, para-valvular leakages, and gradient.

Chest tubes are passed through the two 5 mm miniports; an additional small pericardial drain could be left if needed. This drain will be removed after the pacing wires are removed to avoid the risk of late tamponade. Pericostal stitches are placed to reapproximate the rib if it is dislocated during the initial access. The incision is anatomically closed in layers as per routine using resorbable sutures.

Tips and Tricks

This section will briefly review useful take-home messages and tips that might facilitate ART practices.

- The preoperative evaluation is crucial to establish procedure feasibility, especially at the beginning of the learning curve. It is important to obtain a preoperative computed tomographic angiography (CTA) with "arms down" rather than the standard "arms up" because of the change in height of the intercostal space related to the aortic valve position. CTA should be extended to the abdomen and femoral area to obtain important information on aortic anatomy, atherosclerotic burden, and vessel size to allow safe cannulation. We also use advanced 3D printing modeling to assess anatomical relationships and plan access and port position; however, the standard two-step approach in the analysis of the CTA (i.e., distance from the right sternal border to aorta 10 cm and aorta for at least 50% of the circumference on the right side) is sufficient to assess feasibility.
- Cannulation for CPB might present significant challenges. In case of significantly small femoral accesses or concerns of distal perfusion for underlying peripheral vascular disease, we suggest an interposition graft to allow bidirectional perfusion. Alternatively, it is important to consider peripheral antegrade perfusion via the right axillary artery if central or femoral access is prohibitive or unsafe.
- Arterial and venous femoral vessel anatomy should be carefully assessed as it may complicate cannulation. If the common femoral artery bifurcation is high, we use two 0-Ethibond sutures to suspend the inguinal ligament superiorly, improving exposure for cannulation of the common femoral artery. In smaller arteries, we use a double CV-4 Goretex pledgeted suture placed parallel to the femoral axis, as this is thought to reduce the risk of stenosis when securing hemostasis at decannulation. We recommend using a hydrophilic 0.035 Glidewire with a 6 Fr pigtail catheter in the case of severe aortic tortuosity or atherosclerotic disease in the arch to assist cannula position. The venous anatomy is often poorly assessed, especially for deep groins; thus, providing an adequate "rail" for the cannula position is important, and we suggest an Amplatz wire. It is important to avoid coiling in the RA, misplacement into the RV, or entry into the hepatic vein. If challenges arise, we use a stiffer guidewire

(e.g., SuperStiff or Lunderquist) with a guiding diagnostic catheter or a 6 Fr pigtail catheter to help guide the wire into the IVC.

- Effective cross-clamping is important. We recommend dissection of the posterior aspect of the ascending aorta from the right pulmonary artery branch, depending on the length of the ascending aorta (especially in short aortas or short-neck patients. Aortic clamping and visualization issues could be mitigated via additional pericardial retraction sutures. We suggest temporarily and gently grasping the aorta with a second partial clamp to assist a gentle pull towards the right to accommodate the vessel better between the Chitwood clamp jaws.
- Cardioplegia selection and delivery require some considerations. We suggest antegrade intracellular crystalloid cardioplegia providing up to 2 or 3 hours of safe cardioplegic arrest without redosing, especially at the beginning of the experience. Especially in the case of a sutureless valve implant, it is important to insert the cardioplegia in a high position on the aorta so as to not interfere with the required high aortotomy. Marking the projected sites of cardioplegia and aortotomy with the beating heart is also useful. Moreover, we use Ethibond stitches for the cardioplegia purse-string rather than Prolene, so a Cor-Knot (LSI Solutions, New York, USA) automated system can be used to safely secure hemostasis at the moment of the cardioplegia cannula removal.
- Tailoring the aortic incision to the type of prosthesis implanted is important. Meanwhile, a high aortotomy is crucial for a sutureless prosthesis. In contrast, such an approach can be detrimental for rapid deployment valves in which a J-stick- or italic S-shaped incision extending below the sinotubular junction into the non-coronary sinus might be necessary, considering the size of the prosthesis skirt.
- Avoid instrument and thoracoscope overcrowding after opening the aorta, and use the thoracoscope as a light source, especially when a non-totally endoscopic approach is used. The right coronary sinus annular stitching is the most challenging and should be addressed initially. The “fish-hook” mounting technique helps with the difficult angles and reduces the maneuvering space needed to rotate the needle holder for a backhand stitch. Leveraging on the previously placed stitch is useful to expose the annulus for the following stitch.
- Deairing is a major issue during MICS ART or endoscopic ART approaches. Deairing maneuvers might be inefficient due to the impossibility of direct ventricular manipulation. CO_2 inflation reduces the risk of gaseous emboli, but efficient deairing remains mandatory. It is important to consider that in MICS, especially the totally endoscopic approach, the cardioplegia cannula is not perpendicularly inserted in the aorta; instead of an orthogonal angle, it forms an acute angle. We have elaborated on a protocol to first tilt the table 20 degrees towards the left side of the patient to achieve orthogonality and facilitate air outflow. Next, we obtain a passive heart filling with the clamp on and temporarily holding the LV vent, and then opening the root vent to the venous reservoir (avoid collapsing the ascending aorta if a sutureless valve has been implanted, as this will result in a valve displacement and paravalvular leak [PVL]). Once the root vent line is full of blood, the blood pump flow can be reduced, the cross-clamp removed, the heart unloaded, and the LV vent restarted [18].
- Sutureless valves are prone to early migration or misplacement. Avoid aggressive or extensive root manipulation to check on aortotomy hemostasis. Moreover, using warm blood root infusion (“hot shot”) before cross-clamp removal might not be ideal when using sutureless devices, as it might precipitate prosthesis migration.

Learning Curve

The literature on analyzing the learning curve to perform ART is varied. A consensus has been formulated on 50–65 procedures [8,19]; however, recent reports from a large volume center utilizing cumulative sum analysis (CUSUM) on 300 patients failed to identify and detail a precise curve [20]. In our experience, the challenges that the surgeon should expect when moving from standard full sternotomy to the ART approach are multiple and mainly relate to the angle of access to the valvular plane and the visualization of the annulus. The different angle of approach to the valve exacerbates the difficulties related to the longer working distance.

We recommend first becoming familiar with low- and high-fidelity simulators to reproduce the space constraints encountered in the real scenario and practicing annular stitching before embarking on clinical cases. The use of the thoracoscope, even in the minithoracotomy approach, is crucial as it provides an important light source.

Additional challenges derive from the possibility of valve misalignment with early failure, especially when using a totally sutureless prosthesis [20]. Thus, complete annular decalcification and accurate sizing are crucial in this regard. The use of the thoracoscope can allow for ongoing control of the position of the device before and during the implant. Furthermore, familiarity with the implant of this prosthesis in a full sternotomy setting is advised, particularly regarding the site selection and shape of the aortotomy. On this point, another common pitfall is represented by bleeding from the aortotomy or the root, which can require a second pump run and is often related to a low incision.

Another important cause of complications or conversion to sternotomy is the potential to injure the pulmonary artery during aortic cross-clamping. This problem can be related to inadequate visualization and improper positioning of the Chitwood clamp. We emphasize the importance of initial blunt dissection of the aorta from the right pulmonary artery with the aid of a sucker tip to accommodate the jaws of the clamp. Meanwhile, using another clamp to gently retract the aorta can facilitate cross-clamp positioning.

Nonetheless, carefully selecting patients at the beginning of the experience is crucial. Further, avoid high-risk clinical profiles, and an accurate assessment of the anatomical characteristics is recommended, as described above. Stepwise approaches are the preferred training method, including progressive exposure and introducing the trainee surgeon to the different portions of the procedure with a senior, experienced surgeon [19]. We developed a training protocol that alternates days of practicing on low-fidelity simulators with experience in clinical practice and with cadavers. Considering the very realistic scenario provided, when available, we strongly recommend using cadaveric models to perform all the procedure steps before undertaking an initial case.

Results, Alternatives, and Future Perspective

Despite the predominance of retrospective analyses and the absence of randomized studies, ART has consistently demonstrated safety and efficacy in high-volume centers for aortic valve replacement. Studies have reported low 30-day mortality rates, typically below 1%, and a low incidence of major adverse cardiovascular events, such as stroke, ranging from 0% to 2%. The occurrence of paravalvular leakage ranges between 1 and 3%, and the necessity for permanent pacemaker implantation postoperatively varies, with rates reported between 1% and 5.9%. The conversion rate to sternotomy due to noncontrollable bleeding or difficult access has been reported between 0% and 5%, and the occurrence of re-exploration for bleeding has ranged from 0 to 4%. The length of hospital stay also varies according to several factors across the literature, with an average of 7 days [1–5,19].

Comparative literature on alternative approaches, including standard full sternotomy and mini-sternotomy, derives from retrospective evidence and prevents an unbiased assessment of the relative benefits of one technique with respect to the other.

Generally, ART has shown a safety profile comparable to the standard full sternotomy approach regarding perioperative mortality and short-term complications. Propensity-matched analyses found no significant differences in mortality, stroke, renal failure, or one-year survival. However, ART offered benefits in some studies, including reduced chest tube drainage, lower transfusion rates, shorter mechanical ventilation durations, Intensive care unit (ICU) stays, and overall hospitalization [1–5,19].

When compared to mini-sternotomy, a recent meta-analysis showed no significant differences concerning perioperative mortality, ICU length of stay, cardiopulmonary bypass time, cross-clamp time, total hospital stay, paravalvular leak rates, renal complications, conversion to full sternotomy, permanent pacemaker implantation, or wound infections. However, ART was associated with a lower incidence of stroke, but higher rates of reoperation for bleeding and operation time [21].

Interestingly, only a few studies have reported data on the mid and long-term outcomes of ART compared to other approaches. A study from Reser *et al.* [22] reports one of the longest follow-ups in the literature, with a mean of 69.65 ± 24 months. Survival at 1 and 7 years was 95.8 and 79%, respectively, while freedom from reoperation was 99.5 and 98.7%, respectively. Importantly, freedom from major cardiovascular adverse events at 1 and 7 years was reported at 98.1% and 95.7%, respectively [22]. Other observational analyses have shown a trend of longer-term benefits in the ART group compared to full sternotomy; however, these studies tended to pool ART with mini-sternotomy techniques [3,23]. Instead, an interesting piece of information derives from the congenital literature on bicuspid valve replacement in the pediatric and adolescent populations, which shows no prosthetic malfunction or need for reoperation at a mean follow-up in the ART group of 5.4 years [24].

An emerging alternative to ART regards the right lateral transaxillary (TAX) access with a single incision and direct vision. This approach produced encouraging results with comparable outcomes to full sternotomy [25]. A recent large propensity-matched study has investigated the safety and efficacy of the transaxillary approach compared to ART [25]. While no significant differences were observed in hard outcomes, such as mortality and cardiovascular complications, TAX access was associated with longer bypass times but shorter hospital stays and lower wound-related complications as probable results of avoidance of shoulder grindle injury or rib dislocation [25]. This approach is also thought to allow avoidance of pectoralis muscle division and sacrifice of the right internal mammary, which is often necessary for the minithoracotomy approach. Additionally, the proponents of this approach advocate that the TAX approach offers a more perpendicular access to the plane of the valve, leading to a better visualization of the valve, especially of the right coronary sinus, which might be more challenging in ART settings. There is no evidence of the superiority of one or the other approaches in minimally invasive cardiac surgery (MICS) AVR, and the opinions, center experience, expertise, and preference of a single expert are the main drivers for adopting one approach versus the others. However, ART is amenable to both a totally endoscopic or direct vision approach (while TAX is more often performed via the direct approach) and has seen a more diffuse adoption, with more experience being cumulated up to now.

Notably, given the retrospective nature of the available evidence and the bias related to the frequent pooling of data derived from different techniques, the current quality of the literature and level of proof prevent meaningful comparisons but only permit general considerations. A plethora of confounding factors related to the inherent differences among the various approaches (mini-sternotomy, ART, TAX access, and full sternotomy), including technical difficulty, access-specific complications, local expertise, and volume/outcome relationship, play a significant role and have conspired against a uniform adoption of minimally invasive approaches in aortic valve replacements. Moreover, *ad hoc* randomized controlled studies are warranted in this field. Despite no current randomized evidence conclusively demonstrating the superiority of minimally invasive aortic valve replacement over standard approaches, it is plausible to posit that reducing surgical invasiveness should be the "direction of travel" and that with the emerging data on the long-term survival benefits of surgery versus transcatheter approaches in aortic valve replacement, minimally invasive AVR is likely to play an increasingly important role and may become the benchmark comparator of TAVR in the future, pending further high-quality evidence.

Conclusions

Minimally invasive aortic valve replacement via the anterior right thoracotomy approach is a viable alternative to full or mini-sternotomy with comparable results. Planning with CTA using "arms down" over the standard "arms up" is crucial in the preoperative phase. Particular care should be taken in peripheral cannulation to ensure end-perfusion, especially in cases of peripheral vascular disease. Alternative access on the axillary artery or interposition graft to allow bidirectional perfusion provides viable options. Aortic cross-clamping is a delicate process; thus, care should be taken for an atraumatic clamp position. The type of prosthesis, standard, rapid deployment, or totally sutureless valve, dictates the height of the aortotomy incision, with the latter requiring the highest fat pad incision at least 3.5 cm above the valve plane. Deairing is normally a concern in minimally invasive approaches, and CO_2 insufflation and filling maneuvers are crucial to achieving good results.

Abbreviations

MICS, minimally invasive cardiac surgery; ART, anterior right thoracotomy; TAVR, transcatheter aortic valve replacement; CTA, computed tomographic angiography; IMA, internal mammary artery; RIMA, right internal mammary artery; RSPV, right superior pulmonary vein; TEE, transesophageal echocardiography; CPB, cardiopulmonary bypass; VAVD, vacuum-assisted venous drainage; LV, left ventricle; RV, right ventricle; CS, coronary sinus; PVL, paravalvular leak; DO_2, oxygen delivery.

Availability of Data and Materials

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

Author Contributions

These should be presented as follows: CS, THD, AP, HB, and DR designed the surgical technique. THD, AP, HB, and DR provided help and advice on configuration of the paper. CS and CG performed a literature review and wrote the manuscript. CG edited figures and videos for final publication. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments. The patient provided written informed consent for the use and publication of surgical video footage for academic purposes.

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Conflict of Interest

The authors declare no conflict of interest. Cristiano Spadaccio is serving as one of the Editorial Board members of this journal. We declare that Cristiano Spadaccio had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to Curtis G Tribble.

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