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Surgical strategies to address re-operative complex left ventricular outflow tract and thoracic aortic pathology: Cleveland Clinic children's experience

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Abstract

Background: Complex patients requiring operations on the left ventricular outflow tract, aortic valve, or thoracic aorta after previous repair of aortopathy constitute a challenging group, with limited information guiding decision-making. We aimed to use our institutional experience to highlight management challenges and describe surgical pearls to address them. *Methods:* Forty-one complex patients with surgery on the left ventricular outflow tract, aortic valve, or aorta at Cleveland Clinic Children's between 2016 and 2021 following previous repair of aortic pathology were retrospectively reviewed. Patients with known connective tissue disease or single ventricle circulation were excluded. *Results:* Median age at index procedure was 23 years (range 0.25–48) with median of 2 prior sternotomies. Previous aortic operations included subvalvular ($n = 9$), valvular ($n = 6$), supravalvular ($n = 13$), and multi-level surgeries ($n = 13$). Four deaths occurred in median follow-up of 2.5 years. Mean left ventricular outflow tract gradients improved significantly for patients with obstruction (34.9 ± 17.5 mmHg versus 12.6 ± 6.0 mmHg; $p < 0.001$). Technical pearls include the following: 1) liberal use of anterior aortoventriculoplasty with valve replacement; 2) primarily anterior aortoventriculoplasty following the subpulmonary conus in contrast to more vertical incision for post-arterial switch operation patients; 3) pre-operative imaging of mediastinum and peripheral vasculature for cannulation and sternal re-entry; and 4) proactive use of multi-site peripheral cannulation. *Conclusions:* Operation to address the left ventricular outflow tract, aortic valve, or aorta following prior congenital aortic repair can be accomplished with excellent outcomes despite high complexity. These procedures commonly include multiple components, including concomitant valve interventions. Cannulation strategies and anterior aortoventriculoplasty in specific patients require modifications.

Operations to address the left ventricular outflow tract, aortic valve, or thoracic aorta are frequent, and definitive correction often requires multiple re-interventions. Cardiac re-operation has become more common as life expectancy of patients with CHD has increased due to improvement of surgical imaging, techniques, and outcomes.[1–3] However, multiple previous repairs of challenging congenital pathology pose a series of unique anatomic, physiological, and perioperative challenges that may increase incremental risk for mortality.[2–5] Furthermore, many of these patients have complex histories, multiple diagnoses, and pre-operative risk factors, defining a high-risk heterogeneous cohort that is difficult to study.[2–3] Other factors including loss to follow-up and later presentation are increasingly recognised as detrimental to these patients' risk profiles.[6] Therefore, cataloguing the scope of these anatomies and procedures is critical in order to optimise outcomes in both the short and long term.

We recognised an opportunity given the integrated nature of our quaternary care centre that cares for congenital patients from infancy to adulthood, to provide information regarding discrete surgical strategies that may have the potential to reduce risk of re-operation and optimise repair durability among this challenging population. Specifically, this case series was aimed to accomplish the following three objectives: 1) characterise and group the majority of pathologic entities among patients presenting for left ventricular outflow tract, aortic valve, or aortic surgery after prior complex aortic intervention; 2) describe surgical approaches and techniques that facilitate and expedite successful re-operations among these groups; and 3) trace time-related outcomes and changes in relevant echocardiographic parameters over time.

Materials and methods

Patient inclusion & exclusion criteria

Patients with multi-level aortopathy undergoing left ventricular outflow tract, aortic valve, or aortic operation between 2016 and 2021 at Cleveland Clinic Children's or its affiliated hospital Akron Children's, following repair(s) of congenital aortic pathology, were identified by retrospective chart review of institutional operative records. All patients were operated on by the same group of surgeons. These patients were identified as "complex" based on documentation of complicated anatomy, multiple sternotomies, operative challenges, or difficult re-operation type. Those with known connective tissue disease (i.e. Marfan or Loeys-Dietz syndromes) or single ventricle circulations were excluded. The operation targeting the left ventricular outflow tract, aortic valve, or aorta within our study period is referred to as the "index" operation in this study. We have elected to include all age ranges for this study in order to maximise the number of patients for the study, and also to describe the wide variation in surgical anatomy encountered.

In order to facilitate description of surgical approaches and techniques amenable to specific, more frequently encountered anatomies, patients were categorised based on the anatomic level of aortic pathology that was surgically corrected in cardiac interventions prior to the index surgery. This categorisation was selected to capture the status of each group's aortic anatomy prior to the index surgery. The groupings included post-subvalvular surgery; post-valvular surgery; post-supravalvular surgery; and post-multi-level surgery. "Multi-level" refers to operation(s) that targeted a combination of subvalvular, valvular, and/or supravalvular aortic pathology.

Data collection

Data abstracted for each patient included pre-operative factors included in the Society of Thoracic Surgery Congenital Heart Surgery Database Mortality Risk Model,[7–8] other co-morbidities (e.g. hypertension, smoking history), prior cardiac surgical history, and indication for index operation. Clinical data were collected from review of pre-operative office evaluations, operative reports, post-operative notes, and outpatient follow-up reports. Data relating to the index re-operation including pre-operative symptoms, cardiopulmonary bypass time, aortic cross-clamp time, length of hospital stay, and post-operative follow-up were also abstracted. Surgical techniques used to address specific anatomic challenges (i.e. cannulation strategies and re-do sternotomy), any unexpected intraoperative findings, and technical manoeuvres specific to anatomic entities, were catalogued in detail from the operative reports. The Institutional Review Board approved this retrospective study and waived the need for patient consent (IRB #20-168 approved on 2/11/2020).

Echocardiographic data

Local echocardiographic data were collected and referenced to the index surgery. Pre-operative, post-operative (closest to discharge), and most recent follow-up echocardiogram reports were reviewed to assess the haemodynamic status of the left heart structures over time. Variables collected from each echocardiogram included outflow tract gradient, grade of systolic ventricular function, grade of aortic valve regurgitation, grade of aortic valve stenosis, presence of subvalvular left ventricular outflow tract obstruction, aortic pressure half time, left ventricular end-systolic and end-diastolic dimensions, posterior wall thickness, left ventricular end-systolic and diastolic volume, ejection fraction, left ventricular mass, aortic annulus and aortic root diameters, maximum aortic dimension, mitral valve mean gradient, mitral valve annulus diameter, grade of mitral valve regurgitation, and grade of mitral valve stenosis. Both mean and peak gradients were recorded, and left ventricular volumes were recorded in both m-mode and four-chamber view. In order to describe patients according to their predominant hemodynamic lesions, we divided patients into two groups: 1) primarily aortic regurgitation without obstruction defined as moderate/severe aortic regurgitation with peak gradients <35 mmHg and 2) left ventricular outflow tract/aortic valve/aortic stenosis without primarily aortic regurgitation.

Statistical analysis

Standard summary statistics appropriate for the normality of the data were performed. Time-related survival and re-interventions were traced by the Kaplan–Meier method. Line graphs were used to demonstrate echocardiographic parameters at cross-sectional time points. Paired t-tests compared pre- and post-operative echocardiographic changes in relevant parameters over time. A p-value <0.05 was considered significant.

Results

Forty-one complex patients with biventricular circulation underwent surgery to address the left ventricular outflow tract, aortic valve, or aorta at our institution during the study period after prior congenital aortic operation of any type. The post-subvalvular group included 9 patients (22.0%), the post-valvular group included 6 patients (14.6%), the post-supravalvular group included 13 patients (31.7%), and the post-multi-level group included 13 patients (31.7%). The most common complex operations prior to index surgery included surgical aortic valve replacement/repair (n = 16), subaortic resection (n = 10), arterial switch (n = 7), Ross (n = 3), and truncus arteriosus repair (n = 3). Table 1 showcases a summary of each group's most common anatomies, prior operations, and current index surgery types. Supplemental Table S1 includes a more detailed description of each patient in this study. Unspecified aortic valve replacement/aortic valve repair designates isolated operation on the aortic valve. Several of the operation types included in Table 1 and Supplemental Table 1 include multiple other components of obstruction as follows: a modified Konno procedure includes relief of subaortic stenosis while preserving the native aortic valve, a Konno procedure includes anterior aortic annulus enlargement and replacement of the aortic valve, a Konno-Rastan procedure includes anterior aortoventriculoplasty and replacement of the aortic valve with the aim of relieving all levels of aortic obstruction, a Ross procedure includes replacement of the aortic valve with the native pulmonary valve, a Ross-Konno procedure is a Ross procedure with the addition of enlargement of the left ventricular outflow tract, and a Bentall procedure includes replacement of the aortic root, valve and proximal ascending aorta.

A total of 96 re-interventions addressed cardiac pathologies up to (and including) the index operation with a median pre-index number of sternotomies of two per patient (range 1–6). Most common indications for re-intervention were worsening aortic valve regurgitation, recurrent aortic valve stenosis or left ventricular outflow tract obstruction, and biventricular dysfunction in the presence of important obstruction or valve regurgitation. Table 2 describes age at index operation, follow-up time, and hospital

Table 1. Summary of groups.

Group	Cardiac diagnoses	Common prior surgeries	Common index surgeries
Post-subvalvular (9)	SubAS w/o Shone's (6) AI (4) Shone's Syndrome (2) AV Canal Defect (2) Dilated AA (1) BAV (1)	SubAS resection (7) Modified Konno (3) LVOT membrane resection (2) AV canal repair (2)	SubAS resection (4) Konno-Rastan (4) Unspecified surgical AVr/AVR (2) LVOT resection (1) Aortoplasty (1)
Post-valvular (6)	Shone's Syndrome (3) BAV w/o Shone's (2) AI (2) ToF (1) Dilated AA (1)	Unspecified surgical AVr/AVR (5) Ross (2) ToF repair (1) Balloon aortic valvuloplasty (1)	Unspecified AVr/AVR (2) SubAS resection (2) Bentall (2) Konno-Rastan (1) Ross-Konno (1) LVOT resection (1)
Post-supravalvular (13)	AI (6) TGA (5) TA (3) Dilated AA (5) DORV (2) Supravalvar AS (3) SubAS (2) Aorto-left ventricular tunnel (1) Shone's Syndrome (1)	ASO (6) TA repair (3) RV-PA conduit (re)placement (3) Repair of LV to aortic tunnel (2) AA replacement (1) CoA repair (1) Supravalvar AS repair (1)	Unspecified surgical AVr/AVR/truncal valve replacement (5) RV-PA conduit (re)placement (4) AA replacement (3) SubAS resection (3) Aortoplasty (2) Supravalvar AS repair (1) Ozaki (1) Modified Konno (1) Bentall (1)
Post-multi-level (13)	AI (8) AS w/o Shone's (6) CoA w/o Shone's (5) Shone's Syndrome (3) SubAS w/o Shone's (3) TA (2) Dilated AA (2) TGA (1) Interrupted aortic arch (1)	Valvular + Supravalvular (8) Subvalvular + Valvular + Supravalvular (3)Subvalvular + Valvular (2)	Konno-Rastan or reconstruction (7) Unspecified surgical AVr/AVR (4) SubAS resection (2) Bentall (2) Hemi-arch or AA replacement (2) RV-PA conduit replacement (2)

AA = ascending aorta, AI = aortic incompetence, AS = aortic stenosis, ASO = arterial switch operation, AVr = aortic valve repair, AVR = aortic valve replacement, CoA = coarctation, DORV = double outlet right ventricle, LVOT = left ventricular outflow tract, RV-PA = right ventricle to pulmonary artery, TA = truncus arteriosus, TGA = transposition of great arteries, ToF = Tetralogy of Fallot, w/o = without

Common diagnoses, prior surgeries, and type of index surgery are summarised for each group. Numbers in parentheses indicate the number of patients in each category and are not mutually exclusive. Unspecified aortic valve replacement (AVR)/aortic valve repair (AVr) designates isolated operation on the aortic valve. Several of the operation types included in the above table may address multiple other components of obstruction as follows: a modified Konno procedure includes relief of subaortic stenosis while preserving the native aortic valve, a Konno procedure includes anterior aortic annulus enlargement and replacement of the aortic valve, a Konno-Rastan procedure includes anterior aortoventriculoplasty and replacement of the aortic valve with the aim of relieving all levels of aortic obstruction, a Ross procedure includes replacement of the aortic valve with the native pulmonary valve, a Ross-Konno procedure is a Ross procedure with the addition of enlargement of the left ventricular outflow tract, and a Bentall procedure includes replacement of the aortic valve as well as a component of the aortic root and/or aorta.

length of stay for index surgery for groups by level of aortic pathology targeted by prior operation(s).

Survival and follow-up

Overall survival was excellent at 97.5%, 97.5%, and 90.0% at 3 months, 1 year, and 3 years, respectively (Fig 1). There was one patient (2.4%) lost to follow-up and four total deaths (9.8%) in a median follow-up time of 2.5 years after index surgery. One patient died in the first month, after presenting in cardiac arrest but an autopsy was not performed. Late deaths (3) after 3 years were secondary to cardiopulmonary infections. Specifically, late mortality was due to sepsis from prosthetic aortic valve endocarditis (1), multi-organ dysfunction with acute respiratory failure secondary to bacterial pneumonia (1), and one unknown cause of death. Four patients had complete heart block post-index surgery. Eight patients required re-interventions after index operation, with two patients having heart transplantation. Re-interventions included incision and drainage of sternal wound after wound site infection, excision of aortic and pulmonary valves following Konno-Rastan due to endocarditis, re-do sternotomy for evacuation of a mediastinal haematoma, washout for chest cavity thrombus, first-time tricuspid valve valvuloplasty with ring insertion for severe tricuspid regurgitation, and mitral valve replacement/tricuspid repair for moderate/severe mitral and tricuspid regurgitation following Konno-Rastan.

Echocardiographic variables

The group with primary aortic regurgitation consisted of 12 patients, and the aortic stenosis group consisted of (n = 29). Mean gradients across the outflow tract improved significantly following index surgery for those with stenosis (34.9 ± 17.5 mmHg versus 12.6 ± 6.0 mmHg; $p < 0.001$) (Fig 2a) (Supplemental Table S2). Grade of aortic valve regurgitation similarly improved from mainly moderate/severe grade pre-index surgery to none/trivial/mild grade post-index surgery, as expected given that all but one patient in this group had prosthetic aortic valve replacements (Fig 2b) (Supplemental Table S2).

Overall, diastolic left ventricular diameters at discharge decreased following index surgery (5.02 ± 1.29 cm versus 4.83 ± 1.27 cm; $p = 0.013$). Similarly, median and full data range

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Table 2. Demographics and others.

Group	Pre-index number of sternotomies	Age at index surgery (years)	Duration of hospital stay for index surgery (days)	Follow-up time (years)
Post-subvalvular (9)	2 [1–3]	22 [8–36]	7.5 [5–24]	3.3 [1.4–6]
Post-valvular (6)	1 [1–4]	32.5 [0.25–48]	8.5 [4–20]	2.4 [0.5–3.4]
Post-supravalvular (13)	1.5 [1–3]	19 [0.4–33]	8 [2–233]	2 [0.1–5.5]
Post-multi-level (13)	3 [1–6]	24 [9–35]	8 [5–42]	2.9 [0.1–6.1]
Total (41)	2 [1–6]	23 [0.25–48]	8 [2–233]	2.5 [0.1–6.1]

Median and range are recorded for pre-index number of sternotomies, age at index surgery, hospital duration for index surgery, and follow-up time for each group designated by level(s) of aortic pathology targeted by prior operation(s).

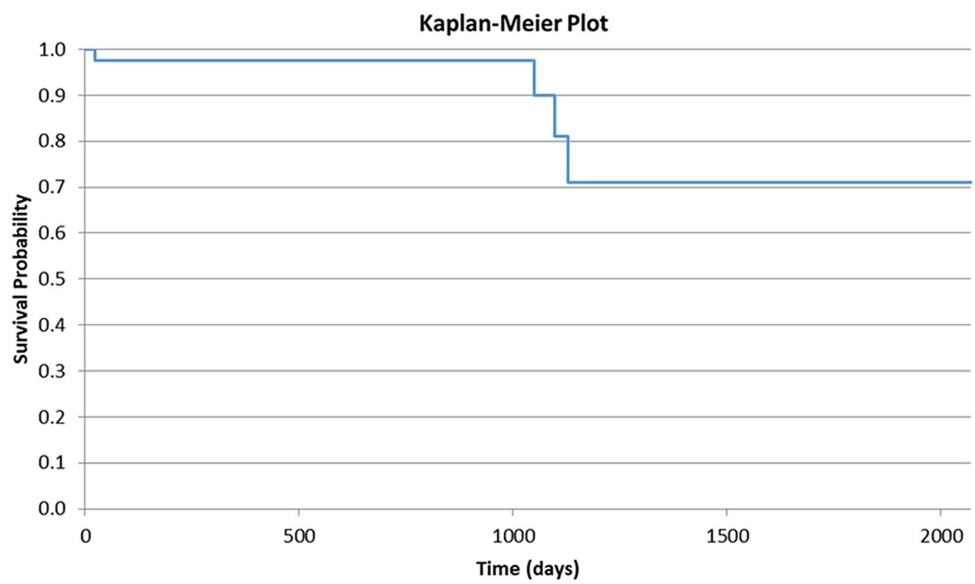

Fig. 1 Kaplan-Meier plot demonstrating the survival probability of the entire cohort (Y-axis) as a function of time (X-axis).

of left ventricular end-diastolic volumes at discharge decreased following index surgery (131.55 [6.4–217] versus 106.00 ml [1.2–243.1]; $p = 0.041$). Left ventricular ejection fraction decreased slightly as well (57% ± 15% versus 53% ± 13%; $p = 0.015$).

Index surgery technical strategies

Technical manoeuvres were tailored to the unique pathology, and our group utilised comprehensive pre-operative planning that was multi-modal. Cross-sectional imaging using CT enhanced by 3D virtual techniques was used to identify sternal re-entry and mediastinal anatomy as well as tailor aortic/left ventricular outflow tract approaches. More recently, we have developed a three-dimensional approach utilising pre-surgical cardiac computed tomographic data of assessing gross anatomical structures related to the triangle of Koch and left ventricular outflow tract in order accurately to predict the location of the ventricular components of the conduction axis related to the aortic root and left ventricular outflow tract. In our early experience applying this novel approach, our occurrence of conduction damage during these higher-risk procedures has decreased below commonly reported incidences. Imaging of the femoral and upper extremity arterial and venous systems were routinely performed to identify, proactively, those patients who were likely to require peripheral cannulation and/or placement of endo-aortic balloon with peripheral retrograde cardioplegia cannula insertion. Meticulous dissection of para-aortic adhesions enabled standard aortic cannulation in 34 patients; however, pro-active peripheral cannulation strategies included one patient with axillary, one patient with femoral, and one patient with multiple peripheral arterial sites (Fig 3). Notably, due to the high number of substernal adhesions, aortic calcification or body habitus, three patients were cannulated in Zone 2 of the arch with a high cross-clamp applied. Venous cannulation was performed in standard bicaval or right atrium dual stage in 38 patients, peripheral cannulation included femoral cannulation or multiple cannulation sites in 1 patient each. Cardioplegia was delivered in the standard fashion with majority of cases utilising both antegrade and retrograde cardioplegia (35/40). Endo-aortic balloon was available, but not used in lieu of aortic cross-clamping in this series.

In addition to the pre-operative planning of complex cannulation and myocardial protection strategies, this patient population often requires multi-level "definitive" left ventricular outflow tract solutions. Our group also has utilised preferential use of anterior aortoventriculoplasty with valve replacement for complex or multi-level left ventricular outflow tract obstruction to adequately address all levels of obstruction rather than using a modified Konno approach or other posterior aortic annular enlargement techniques. [9,10] In order to reduce the risk of heart block, we have described directing the primary anterior aortoventriculoplasty leftward to the left ventricular apex, following the subpulmonary

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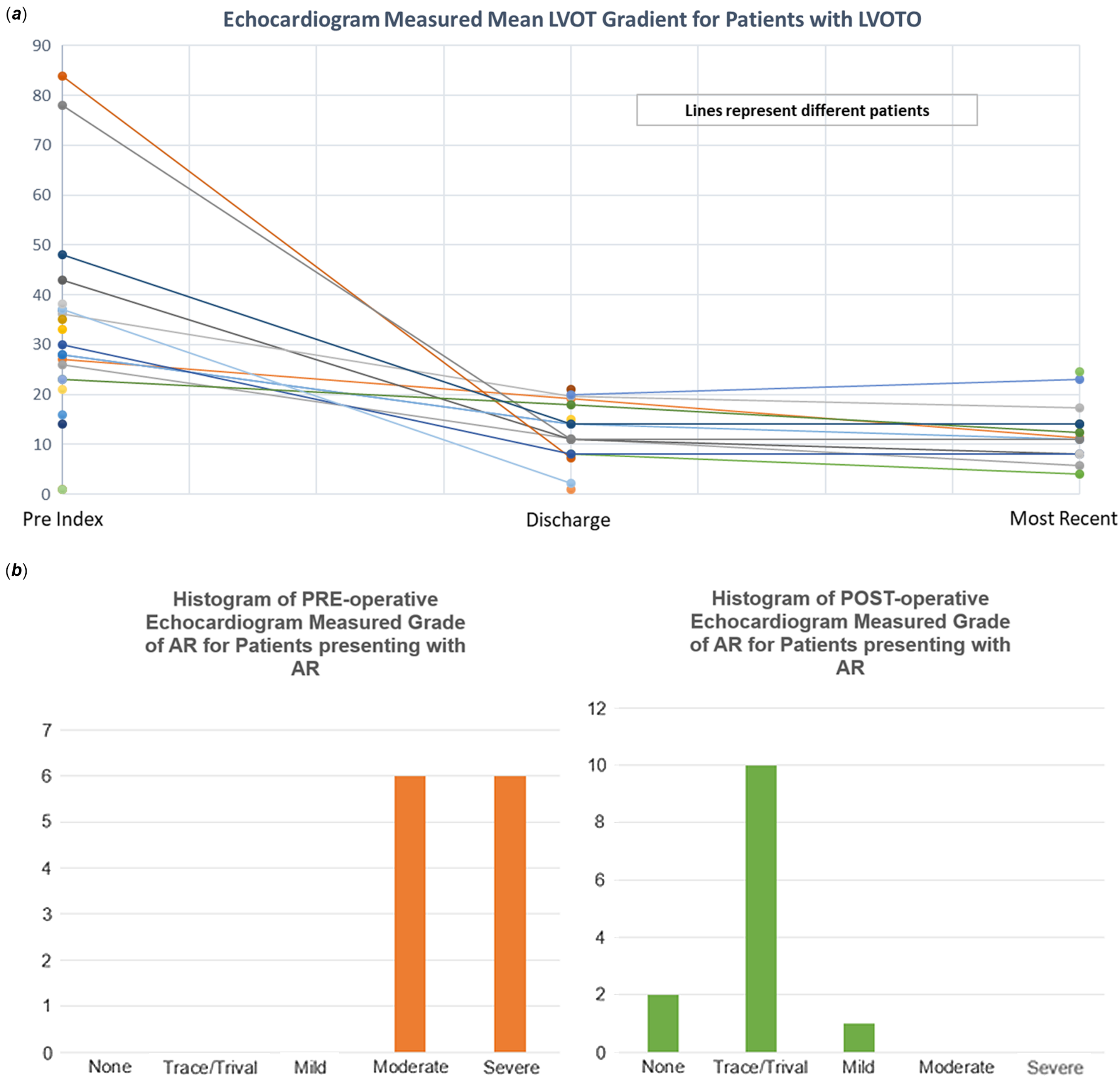

Fig. 2 (***a***) Longitudinal trajectories of the measured echocardiographic mean gradient acriss the left ventricular outflow tract for patients at baseline (pre-index), discharge after index procedure (discharge) and at most recent follow-up; (***b***) Orange histograms demonstrate the number of patients with different degrees of aortic regurgitation (AR) pre-operatively and the green histograms demonstrate the number of patients in different degrees of AR postoperatively.

conus, for most anatomic pathologies, except for post-arterial switch patients, in which this incision is more vertical.

Choice of valve prosthesis and anticoagulation strategy

In general, bioprosthetic aortic valve replacement has been the preference at our centre for some time for adult patients, women of childbearing age, albeit with known limitations of age-related valve durability.[11] We have previously demonstrated in-hospital outcomes including stroke, infection, re-operation for bleeding and risk-adjusted survival at 18 years (60% bioprosthetic, 58% mechanical, $p = .2$) were similar between bioprosthetic and mechanical valves in a propensity-matched comparison of 527 patients.[11] For young patients (and the notion of "young" is certainly not well-defined), we would encourage mechanical valve placement with an On-X valve™ to lower the need for full anticoagulation. Our anticoagulation strategy is to utilise antiplatelet agents for 6 months following bioprosthetic aortic valve replacement and warfarin for On-X valves to maintain an international normalized ratio between 2 and 2.5 depending on other risk factors.

Selection criteria and decision to offer the Ross procedure was referring cardiologist, patient and, surgeon-specific, have been era dependent at our centre. Initially after introduction, Ross was

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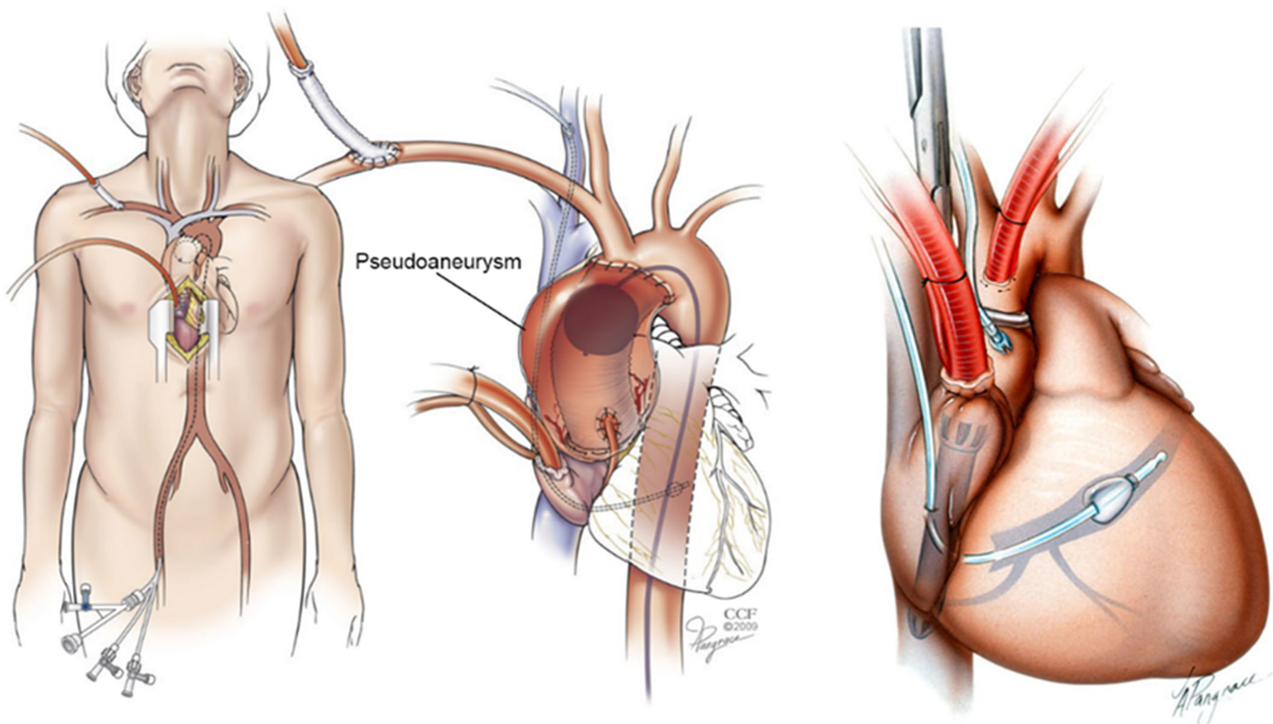

Fig. 3 Schematic demonstrating a complex cannulation and perfusion strategy used for one of the patients.

offered less selectively. Similar to other centres, we have become more selective regarding patient suitability for the Ross procedure which has been reflected in the improved survival at our centre with no deaths since 2000. Our ideal patient for Ross procedure includes younger patients (less than 55 years) with isolated aortic stenosis versus aortic regurgitation (AR) or mixed aortic stenosis/AR pathology, including patients with bicuspid valves and mildly dilated roots. Moreover, we would recommend a Ross operation for patients with good pre-operative functional status, though there are no absolute exclusions in terms of age or clinical features. Patients with a bicuspid aortic valve or predominant aortic regurgitation versus stenosis may have worse autograft durability over time and are not favourable for the Ross procedure if the aortic annulus and root or ascending aortic dilation are dilated or with suspected aortopathy. The Ozaki procedure is gaining traction at our centre as well. Shared decision-making with the patient and the family are critical for any prosthesis choice, and this is routine before any selection for valve type is made.

Discussion

With improving survival after complex congenital cardiac surgery over the last three decades, more patients are presenting for re-operations. This case series specifically describes the clinical outcomes of complex operations involving the left ventricular outflow tract, aortic valve, or thoracic aorta after previous aortic operation(s) in this heterogeneous patient population. There are various factors which make these procedures inherently high-risk. First, patients may present with multiple previous operation as recurrence is common in subaortic and supra-aortic lesions.[2] Our patients underwent 96 total re-interventions to address cardiac lesions prior to (and including) index operation, with a median number of two pre-index sternotomies per patient (range 1–6). Second, suboptimal relief of subaortic obstruction in previous operations would automatically translate to a need for further re-do interventions. Re-operations including those on the left ventricular outflow tract from prior reports have shown 7–10% early mortality and 24% incidence of major morbidity.[2,12] Small size of the aortic annulus and limited accessibility due to anatomical factors also contribute towards the difficulty in achieving required left ventricular outflow tract relief at an early age.[13] Third, previous repair of cardiac lesions, for example, transposition of great arteries and truncus arteriosus, make approach to the left ventricular outflow tract, aortic valve, or aorta more challenging due to overlying pulmonary arteries, coronary anastomoses or extra-cardiac conduits. Fourth, abnormal septal attachments of the mitral valve contribute to left ventricular outflow tract obstruction in some patients and may not have been fully addressed.[14] Finally, this heterogeneous patient population represents a cohort at relatively higher risk for atrioventricular block and need for permanent pacemaker insertion compared to many other common CHD populations.[15]

Despite these complexities, we have demonstrated excellent outcomes for these patients with a survival of 97.5% and 90.0% at 1 and 3 years, respectively, compared to other previous reports.[2,12] Our approach towards this challenging group of patients is to aim for adequate relief of obstruction at all levels. We have favoured using anterior aortoventriculoplasty with valve replacement using our modified incision to completely address multi-level obstruction. This approach reduces the risk of heart block as noted in our prior report detailing the Konno-Rastan operation.[16] Moreover, we have also found that anterior enlargement of the aortic annulus by aortoventriculoplasty is more versatile than other conventional approaches because it also provides direct exposure of the inter-ventricular septum and mitral valve.

We achieve septal enlargement by a leftward vertical incision to avoid conduction tissue and use generous pericardial patches to

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achieve enlargement of the sub-valvular area and aortic annulus. We use continuous sutures for patch placement and valve replacement and use teflon pledgets at transition points. As anterior aortoventriculoplasy causes the left ventricular outflow tract to bulge into the right ventricular outflow tract, the subpulmonary area should also be enlarged antero-laterally by a generous pericardial patch to avoid right ventricular outflow tract obstruction. Lastly, maximising the prosthesis effective orifice area for the patient's body habitus is crucial to prevent patient-prosthesis mismatch and early re-intervention; generous pericardial patch allows enlargement of the right ventricular outflow tract to accommodate the larger prosthesis.

In view of the lengthy nature of these procedures, we endeavour to minimise cardiopulmonary bypass time by carrying out the majority of dissection before administration of heparin. Pre-operative planning facilitated by non-contrast CT imaging of the mediastinum improves the safety of sternal re-entry,[17] and we tend to carry out most of the retrosternal dissection under direct vision using a Rul-tract retraction system ™ before sternal opening. For patients with porcelain aortic or sternovascular adhesions, femoral and axillary cannulation sites were prepared pre-operatively. Meticulous attention towards myocardial protection is also key to achieve good clinical outcome, and we utilise both antegrade blood cardioplegia combined with intermittent administration of retrograde blood cardioplegia through direct cannulation of the coronary sinus.

For those patients primarily with aortic valve disease, we have adopted an approach complimented by cardiac CT for detailed pre-surgical planning of aortic valve repair, reconstruction, and replacement strategies.[18] This has also allowed us better to address our incidence of conduction damage and need for permanent pacemaker insertion following these higher-risk surgeries. A large multi-centre study reported incidences between approximately 5–15% depending on the complexity and need for subvalvular manipulation.[15] Our current report cites an incidence of approximately 10%, in keeping with reported values of this higher-risk population. In applying a predictive approach of estimating the location of the ventricular components of the conduction axis and how they relate to the aortic root, we have had a 0% incidence in our 13 most recent surgical cases although those cases were not available for descriptive analysis in this study. This approach uses understanding of the relationship of the triangle of Koch to the left ventricular outflow tract; specifically, the inferior pyramidal space, inferoseptal recess, crest of the muscular inter-ventricular septum, and inferior margin of the membranous septum, and how variation in these components relate to variation in the conduction axis. [19–21]

Exposure to the aorta should be adequate even if it entails division of overlying pulmonary arteries or in situ conduits. In cases of previous arterial switch procedure in which a LeCompte was performed, generally the right pulmonary artery lies anterior to the aorta and division of the right pulmonary artery, dissecting it off the coronary anastomoses carefully and swinging the main pulmonary artery leftwards provides excellent exposure to the entire aortic root. After completion of the aortic procedure, the right pulmonary artery can be repaired by direct anastomosis or using a patch angioplasty. Similarly, a right ventricle to pulmonary artery conduit lying in front of the aorta, as frequently encountered in previous truncus arteriosus repair or Ross procedure patients, is often "due" for replacement due to important stenosis or regurgitation, and total removal of the conduit greatly facilitates aortic exposure.

In summary, this study shows the spectrum of complex pathologies and anatomic entities we have encountered at our centre necessitating re-operations to address the left ventricular outflow tract, aortic valve, and proximal thoracic aorta. Although this is a limited, heterogeneous population, we demonstrate several techniques that can be employed to deal with frequent perioperative challenges. Intermediate results are promising, and most importantly, outflow tract gradients appear to be stable following hospital discharge, which may suggest long-term durability using our comprehensive approach.

Limitations

There are inherent limitations to a descriptive case series, including the heterogeneity of the included cohort, limited sample size, and need for longer-term follow-up. We have outlined our own approach to operative techniques for these patients, but further studies are required to directly compare outcomes of our techniques to those of other institutional approaches. Given that our objectives were to highlight some of our operative techniques for this complex cohort and showcase successful mid-term outcomes, we have also elected to minimise statistical analysis. Additionally, we recognise that including a broad age range makes this cohort difficult to study given the differing considerations for operations based on age group. However, we have elected not to limit inclusion of patients by age in order to maximise the number of patients included in the study and to be able to follow patients' operation and re-operation types over time.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S1047951122003936

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