

Mitral valve repair using leaflet expansion and subpartial annuloplasty in children



Per Wierup, MD, PhD,^{a,b} Jens Johansson Ramgren, MD, PhD,^a Johan Sjögren, MD, PhD,^b Kiet Tran Phan, MD, PhD,^a Igor Zindovic, MD, PhD,^b Shahab Nozohoor, MD, PhD,^b Lea Christerson, MSc,^{c,d} and Nina Hakacova, MD, PhD^c

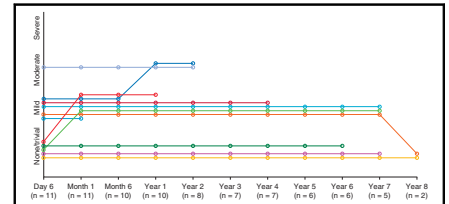
ABSTRACT

Objective: Mitral valve reconstruction in the pediatric population is a challenge due to the frequent combination of annular dilatation and leaflet restriction and the need for growth. We present a novel strategy using leaflet expansion and subpartial annuloplasty with polytetrafluoroethylene reinforcement.

Methods: From January 2014 through May 2021, 11 children aged 5 months to 14 years (median, 24 months) underwent elective mitral valve repair due to severe mitral valve regurgitation. The mitral valve abnormalities included congenital malformations (n = 7), postoperative leakage following commissurotomy (n = 1), and functional mitral valve regurgitation due to dilated cardiomyopathy (n = 3). Surgery consisted of leaflet expansions with autologous, untreated pericardium and subpartial annuloplasty with polytetrafluoroethylene reinforcement.

Results: All children survived their surgeries with uneventful postoperative courses, except for 1 patient who needed an early reoperation to resolve a functional stenosis due to a spinnaker phenomenon. At discharge, mean gradient was 3.5 ± 3.9 mm Hg, with trivial mitral regurgitation in 9 patients (82%). All patients were alive and asymptomatic during the median follow-up of 3 years (range, 1-7 years). Their echocardiographic data showed a mean transmitral gradient of 4.4 ± 1.7 mm Hg and remained unchanged. Residual mitral valve regurgitation was trivial or mild in 9 patients (82%) and moderate in 2 patients (18%).

Conclusions: Leaflet expansion with autologous pericardium and subpartial annuloplasty with polytetrafluoroethylene reinforcement for mitral regurgitation in the pediatric population gives stable and satisfactory results both early and at intermediate follow-up, permitting growth of the mitral valve. (JTCVS Techniques 2024;23:74-80)



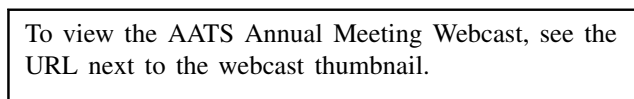
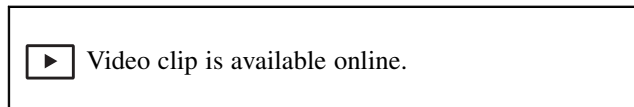
Mitral regurgitation over time depicted for each patient.

CENTRAL MESSAGE

Leaflet expansion with autologous pericardium and subpartial annuloplasty for mitral regurgitation in the pediatric population provides satisfactory and stable intermediary results.

PERSPECTIVE

Mitral valve reconstruction in children is challenging due to leaflet restriction and the need for growth. Leaflet expansion and subpartial annuloplasty with polytetrafluoroethylene reinforcement gives satisfactory and stable results at intermediate follow-up. The addition of a subpartial annuloplasty attenuates the risk for a spinnaker phenomenon while permitting growth of the mitral valve.



From the Departments of ^aPediatric Heart Surgery, ^bCardiothoracic Surgery, and ^cPediatric Cardiology, Skane University Hospital, Lund, Sweden; and ^dDepartment of Biomedical Engineering, Lund University, Lund, Sweden.

Read at the 2023 American Association for Thoracic Surgery Mitral Conclave Workshop New York, New York, May 4-5 2023.

Received for publication July 4, 2023; revisions received Oct 3, 2023; accepted for publication Oct 17, 2023; available ahead of print Oct 30, 2023.

Address for reprints: Per Wierup, MD, PhD, Departments of Pediatric Heart Surgery and Cardiothoracic Surgery, Skane University Hospital, 22185 Lund, Sweden (E-mail: wierup.per@gmail.com).

2666-2507

Copyright © 2023 The Author(s). Published by Elsevier Inc. on behalf of The American Association for Thoracic Surgery. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

<https://doi.org/10.1016/j.xjtc.2023.10.020>

Abbreviations and Acronyms

AV	=	atrioventricular
MR	=	mitral valve regurgitation
PTFE	=	polytetrafluoroethylene

Mitral valve replacement in small children is hampered by the obvious patient–prosthesis mismatch leading to left ventricular outflow tract obstruction and frequent atrioventricular block. In cases where this is required, pacemaker insertion leads to left ventricular dysfunction and heart failure. Hence, full mitral valve replacement carries an overall dismal prognosis, especially in younger children with a perioperative mortality between 11% and 36%¹⁻³ and as high as 52% in children younger than age 2 years.⁴ Hence, mitral valve repair is an appealing alternative that avoids most of the complications related to valve replacement. However, mitral valve repair in the pediatric population is a challenge due to the frequent combination of type I and IIIb dysfunction (ie, annular dilatation and leaflet restriction). Heterogeneity of the atrioventricular (AV) valve anatomy adds to the complexity of the procedure, and the need for growth potential further challenges the available repair techniques. Taking all these factors into account, we have developed a strategy for mitral valve reconstruction using leaflet expansion and subpartial annuloplasty with polytetrafluoroethylene (PTFE) reinforcement. The purposes of this study were to describe the surgical technique and to present our initial short- and midterm results following the procedure.

METHODS

This was a single-center, retrospective, observational study, approved by the Swedish Ethical Review Authority 2017/559 dated April 19, 2017.

Study Population

Study subjects were identified by retrospective review of charts of all patients referred to our institution for surgical treatment of mitral insufficiency between January 2014 and May 2021. We included all patients younger than age 18 years with echocardiographically confirmed severe mitral regurgitation (MR) or moderate MR with hemodynamic instability. Our strategy was leaflet expansion and subpartial annuloplasty with PTFE reinforcement.

The study included 11 patients (6 women and 5 men) undergoing elective atrioventricular valve repair with leaflet expansion and subpartial annuloplasty with PTFE reinforcement between January 2014 and May 2021. The follow-up period was 0.3 to 8 years (median, 6.5 years). Median age of patients at the time of surgery was 2 years (range, 2 months–14 years) and the median weight was 8.9 kg.

Valve Pathology

The etiology of AV-valve disease in all patients included annular dilatation and restriction of the posterior leaflet. Four patients also had undergone previous correction for congenital AV malformation (common AV valve in 2 patients and mitral valve arcade in 2 patients) and postoperative residual MR after commissurotomy ($n = 1$). Seven patients had associated congenital heart defects, including coarctation of aorta, ventricular septal defect,

atrioventricular canal defect, cardiomyopathy, and atrial septal defect. Two patients had mixed mitral stenosis and regurgitation, whereas 9 patients had isolated MR.

Surgical Procedures

Typically, these patients displayed a restricted posterior leaflet together with an annular dilatation. The restricted posterior leaflet was addressed by detaching the entire posterior leaflet close to the annulus leaving the secondary chords on the detached leaflet while the restricted chords were cut. This incision was carried beyond each commissure. In general, these children had restriction of their posterior leaflet secondary to a severe annular dilatation. In some instances, a few isolated chords were pathologically restrictive, and they were divided regardless of being primary or secondary chords. Division of isolated truly restricted chords did not create a prolapse and hence, we did not add PTFE chords there. However, some patients had a true prolapse of the anterior leaflet that was addressed by adding PTFE chords. A generous, nontreated autologous pericardial patch was then sutured in place along the annulus with a running suture. We prefer to start from the lateral aspect and suture the posterior side first. The patch was oriented so that the smooth surface faced the atrial aspect of the heart. The anterior part of the patch was then sutured to the posterior leaflet, which was expanded in such a way as to preserve the normal chords.

Partial annuloplasty is a generally accepted term meaning a posterior annuloplasty from trigone to trigone. This does not work in children because it does not permit sufficient growth. Hence, our annuloplasty is substantially less circumferent and we want to stress that by adding the prefix “sub.” The annuloplasty is made of a 0.4-mm thick strip of PTFE, and the length is determined by the distance between the points immediately below the commissures in the relaxed heart. It is sutured in place with interrupted, non-resorbable sutures that are passed both through the pericardium and the annulus in an oblique way, passing the needle through the base of the pericardial patch and move the needle obliquely exciting on the annulus.

We favor using a subpartial annuloplasty made from a strip of PTFE, which increases the coaptation between the leaflets. Moreover, the limited extent of the band, positioned a bit below the commissures, enables subsequent growth of the valvular apparatus while attenuating the risk for spinnaker phenomenon by altering the flow through the mitral annular orifice plane.

Segmental prolapse is addressed by adding PTFE chords, which are placed through the fibrous tip of each corresponding papillary muscle head and sutured in place near the free edge of the prolapsing segment of anterior mitral leaflet. We place them from the ventricular aspect to the atrial side and back so that the knot connecting the 2 strands ends up on the ventricular surface. Typically, the medial aspect of the leaflet is addressed with 1 loop and the lateral part with another loop.

The length of these neochords are adjusted to permit the free margin to reach its corresponding annular insertion in the relaxed cardioplegic heart. Although the neochords may appear long when the heart is relaxed, this strategy normally achieves a perfect length in a working heart. Determining the length of the artificial chords is among the key questions when using PTFE chords. Based on our extensive experience on this matter in adults we use the same strategy in children.

Study Variables

The primary end point was survival and the secondary end points were MR over time, mean mitral gradient over time, and growth. Baseline patient characteristics, preoperative echocardiography data, intraoperative surgical assessment of the valve, and postoperative clinical and echocardiographic data were collected from the electronic medical record system and imaging database.

Clinical status and data from the transthoracic echocardiography were analyzed at the time of discharge; 1, 3, and 6 months postoperatively; and yearly thereafter. Mitral valve regurgitation, transvalvular gradients, right and left ventricular function, and pulmonary artery pressures were recorded. Mitral valve stenosis and regurgitation was graded as 1 = no or

trivial, 2 = moderate, and 3 = severe.⁵ Adverse events during follow-up were death due to any cause, thromboembolic episodes, bleeding complications, infective endocarditis, and reoperation.

Statistical Analysis

Continuous variables were presented as mean \pm SD and/or median (interquartile range [IQR]) depending on distribution of data. Categorical variables were shown as number and percentage of the sample. Statistical analysis relied on SPSS statistical software version 24 (IBM-SPSS Inc).

RESULTS

Baseline and perioperative characteristics of the study population are displayed in [Table 1](#).

Surgical Techniques

The posterior leaflet was augmented with nontreated autologous pericardium in all but 1 patient, where because of anatomical variation, the anterior leaflet was expanded instead. All repairs were supported with annuloplasty. Nine patients had subpartial annuloplasty made by a strip of PTFE, and 2 patients had full conventional annuloplasty due to the patients' size. Chordal procedures (excision of chordae or PTFE neochordae) were carried out in 2 patients and cleft closures with sutures in 2 patients.

Perioperative Outcomes

The median cardiopulmonary bypass and aortic cross-clamp duration of the entire cohort were 164 minutes (range, 106-205 minutes) and 88 minutes (range, 80-108 minutes), respectively. The median ventilation time was 15 hours (range, 2-288 hours) and mean intensive care unit and hospital stay were 2 days (IQR, 1-30 days) and 8 days (IQR, 6-43 days), respectively.

Early Mortality/Morbidity

All children survived their surgeries with an uneventful postoperative course, except for 1 patient who needed a

reoperation 16 days after surgery. The indication for this procedure was a functional stenosis due to a spinnaker phenomenon, which was corrected by creating neochordae with PTFE to the posterior leaflet. These chords were made purposely short to attenuate the spinnaker phenomenon. The subpartial annuloplasty was not performed in this patient, being the first in this series.

Follow-up and Late Mortality

All patients were alive and asymptomatic during follow-up (median, 6.5 years; IQR, 0.3-8 years). The mitral regurgitation decreased in all patients from severe in 8 patients (73%) and moderate in 3 patients (27%) to moderate in 2 patients (18%) and trivial in 9 patients (82%). The MR remained trivial or mild in 9 patients (82%) and remained moderate in 2 patients (18%). The development of MR over time is depicted in [Figure 1](#). At discharge, the mean gradient was 5 ± 2 mm Hg. At final follow-up (range, 0.3-8 years) the mean transmitral gradient remained normal (4.4 ± 1.7 mm Hg) in all patients. The mean gradient over time is depicted in [Figure 2](#). There were no late events in terms of thromboembolic episodes, bleeding complications, infective endocarditis, or reoperations. All but 1 child followed their expected weight curve ([Figure 3](#)). That patient had an associated feeding disorder, and difficulties gaining weight was not directly related to the AV valve regurgitation.

DISCUSSION

Principal Findings

Leaflet expansion with autologous pericardium and subpartial annuloplasty with PTFE reinforcement for MR in pediatric populations provides satisfactory and stable results both early and at intermediate follow-up. We demonstrated a satisfactory grade of residual MR, mitral gradient, and normal growth ([Figure 4](#) and [Video 1](#)).

Technical Aspects

Leaflet augmentation for restricted posterior leaflet and annular dilatation. The posterior leaflet in these patients is functionally insufficient in terms of size due to the restriction. A very tight annuloplasty would not be sufficient and would prevent growth. Initially, our strategy for this entity with restricted posterior leaflet and annular dilatation was to create a large expansion of the posterior leaflet with autologous nontreated pericardium. Carpentier and colleagues⁶ introduced this technique more than 30 years ago and Acar and colleagues⁷ showed that the addition of leaflet augmentation annuloplasty to annuloplasty improved results for repair in rheumatic valve disease. This technique utilized glutaraldehyde-treated autologous pericardium, and subsequent articles reported excellent outcomes for this type of augmentation with anterior⁸ as well as posterior⁹ expansion for restricted leaflet pathology in

TABLE 1. Baseline and perioperative characteristics of the study population (N = 11)

Characteristic	Result
Age (y)	2 (0.8 to 5)
Female sex	6 (55)
Weight (kg)	10.2 (6.2 to 16.8)
Weight compared with normal (SD)	-1.5 (-2.3 to -1.15)
Height (cm)	80 (66 to 104.5)
BSA (m ²)	0.46 (0.36 to 0.70)
Cardiopulmonary bypass time (min)	164 (106 to 205)
Crossclamp time (min)	88 (80 to 108)
Time on ventilatory support (h)	18 (4 to 24)
ICU stay (days)	2 (1 to 4)
Length of hospital stay (d)	8 (7 to 28)

Values are presented as median (interquartile range) or n (%). BSA, Body surface area; ICU, intensive care unit.

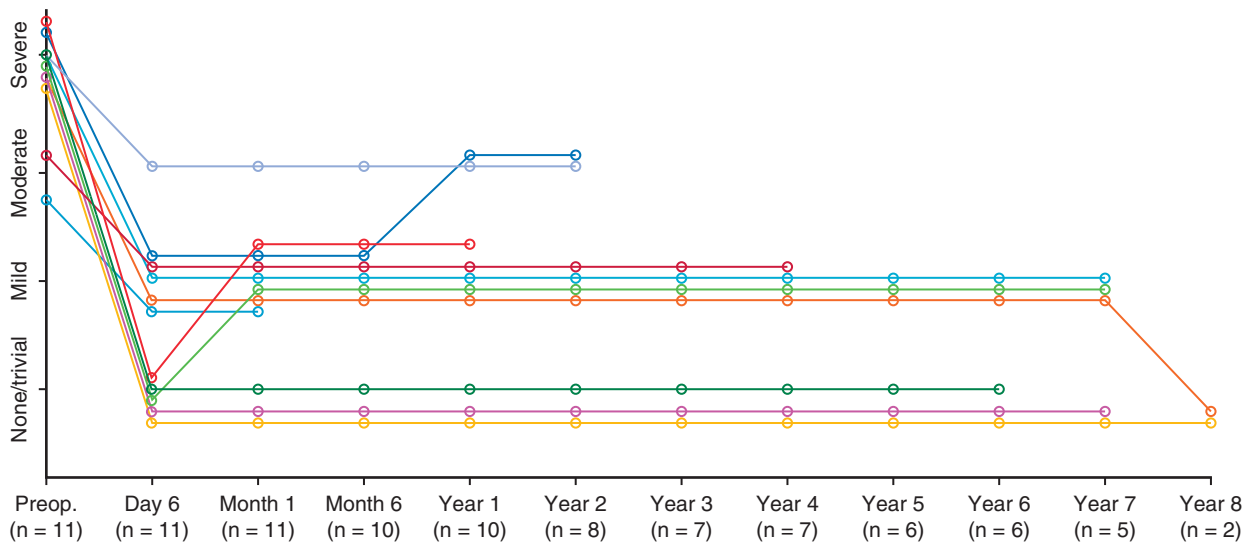


FIGURE 1. Regurgitation grade of the mitral valve over time for each patient.

combination with annular dilatation. Both articles used either autologous or bovine pericardium treated with glutaraldehyde. Subsequent patch calcification and progressive stenosis remains a concern when using glutaraldehyde. More recently, Gammie and colleagues¹⁰ reported excellent long-term performance for fresh autologous pericardium in the setting of endocarditis. Given the size of our patients, we elected to use nontreated autologous pericardium to maintain the pliability of the leaflets. While expanding the posterior leaflet, the leaflet is detached, and truly restricted chords are divided but most are preserved. Performing many mitral repairs in children and especially adults, we believe that the secondary chords are important for the cooperation between the mitral valve and the left ventricle.

If they are not truly restrictive, we tend to preserve them. Most of the restriction in these patients is secondary to severe annular dilatation.

The leaflet augmentation would compensate for both the restricted posterior leaflet as well as the annular dilatation, thereby creating a generous zone of coaptation. In the first patient in this series, an adequate zone of coaptation was verified by the intraoperative saline test, and the valve opened nicely in the relaxed state. However beautiful the intraoperative saline test looked, the patient developed a spinaker phenomenon resulting in a functional stenosis. We solved this issue by adding PTFE chords, which pulled the posterior leaflet further down into the ventricle. This was adequate but not perfect and this patient is the 1 with

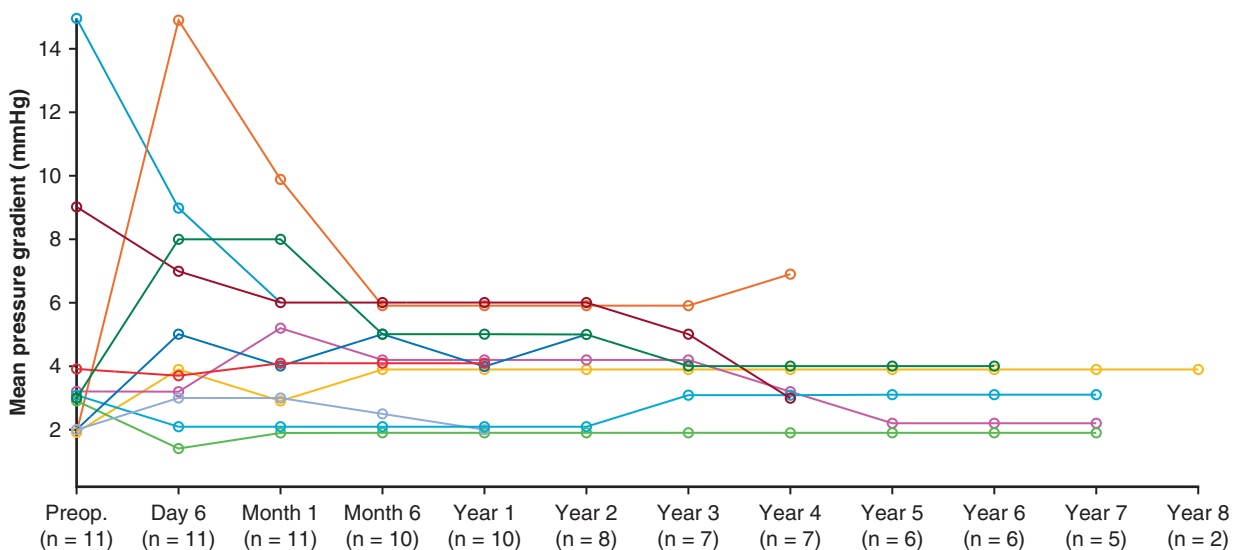


FIGURE 2. Mean gradient over time for each patient.

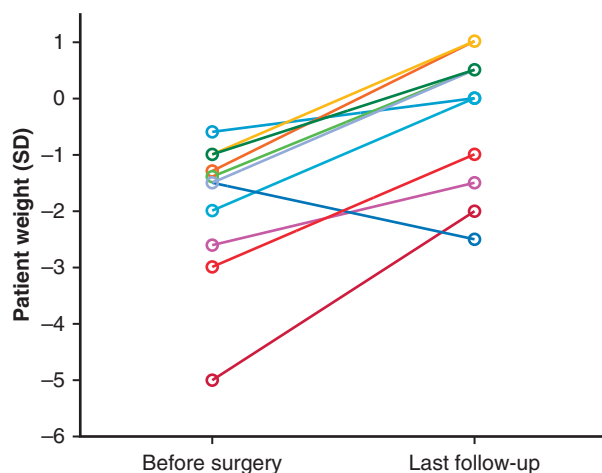


FIGURE 3. Relative weight of each patient before surgery and at last follow-up. *SD*, Standard deviation.

the highest gradient. After analyzing the pathophysiology behind the spinnaker phenomenon, we realized that the inflow through the very large mitral annular orifice caught the expanded posterior leaflet and lifted it toward the anterior leaflet rendering the resulting orifice functionally stenosed. Therefore, to alter the flow through the mitral annulus, we added an annuloplasty. An annuloplasty prevents normal growth, which is essential in the pediatric population. Moreover, prosthetic rings should be avoided due to the scarring tissue caused by the ring and hence, plication of the posterior annulus with pledgeted sutures has been suggested but with suboptimal results.¹¹ To balance this equation, we decided on a moderate-sized posterior leaflet augmentation adding only a subpartial annuloplasty made from a strip of PTFE. Our belief was that this would attenuate the risk of spinnaker phenomenon by altering the flow through the mitral annular orifice plane. Moreover, our hope was that the limited extent of the band, a bit below the commissures would enable subsequent growth. The annuloplasty itself did not need to substantially lift the posterior leaflet toward the anterior because we can balance the zone of coaptation with an adequate size of leaflet expansion to achieve a smooth surface of coaptation. The height is determined by the need to expand the posterior leaflet enough to create a zone of coaptation in the relaxed heart. See [Video 1](#).

We have so far not performed reoperation on any of the patients with PTFE annuloplasty band in this series, but we frequently use PTFE patches for ventricular septal defect and sometimes atrial septal defect and they are normally covered with endothelium but not a thick scar. Our belief from adult experience is that commercial annuloplasty band will have pannus formation. Although this may not be so thick, the profile of commercial bands are much higher and thicker than the 0.4-mm PTFE band. Hence, we prefer our tailored PTFE band. Moreover, in

most of the children a standard annuloplasty band would be far too long for the distance between a little bit below each commissure. We believe that specific area of the annulus will not grow, but the rest will, and we have seen very stable gradients over time in our growing patients.

Segmental Prolapse

We address segmental prolapse by adding PTFE chords. This is most commonly needed for the anterior leaflet. Taking advantage of our significant experience with leaflet preservation using artificial chords made of PTFE in the adult population, we have used this technique in children with stable results. Although the PTFE chords do not increase in length over time, all the remaining structures of the mitral apparatus do grow. This seems to balance the leaflets because we have not seen any progressive residual MR in patients who have received artificial chords.

Early Results

All children survived their surgeries with uneventful postoperative courses, except for the 1 patient who needed an early reoperation for functional stenosis due to a spinnaker phenomenon. Our strategy with moderate-sized leaflet expansion, subpartial annuloplasty, and artificial chords for segmental prolapses resulted in excellent hemodynamic outcome with minimal residual MR and a low transmitral gradient.

Intermediate Results

All patients were alive and asymptomatic at follow-up without the need for subsequent reintervention or pacemaker. They followed their expected growth and their valve function remained stable with no increase in residual MR and stable mean gradient. Although this is a small series, we believe that we have developed a balanced approach for this complicated entity.

Strengths and Limitations

Although this is a single-center, observational study with a limited number of patients, it might be the largest experience using a combination of moderate-sized leaflet expansion in combination with a subpartial annuloplasty. Moreover, all patients were followed thoroughly using standardized protocols, and owing to the structure of the Scandinavian health care system, no patients were lost to follow-up. Our program for pediatric cardiac surgery is substantially large due to the centralized treatment for congenital heart defects in Sweden, providing surgeons extensive experience in all aspects of mitral valve repairs from both the adult and the congenital program.

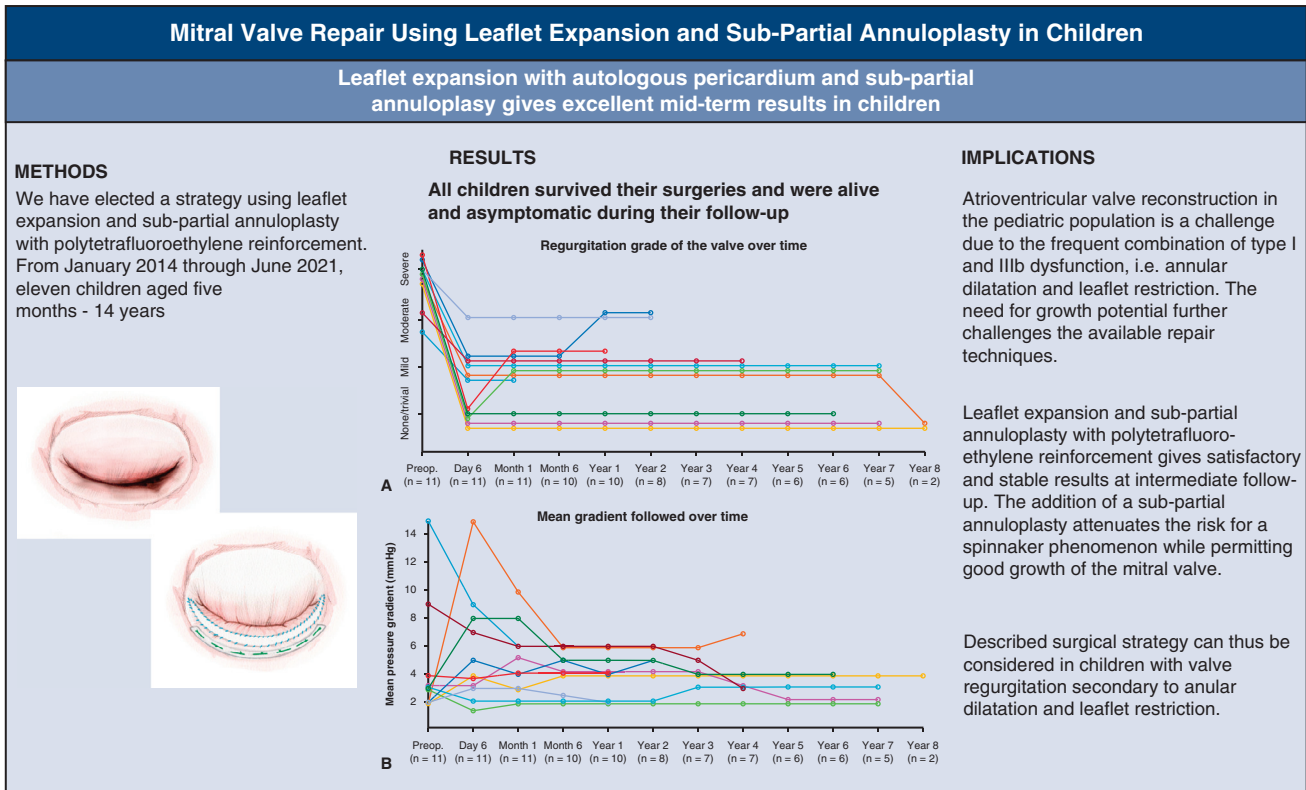


FIGURE 4. Graphical abstract depicting the study’s methods, results, and implications.

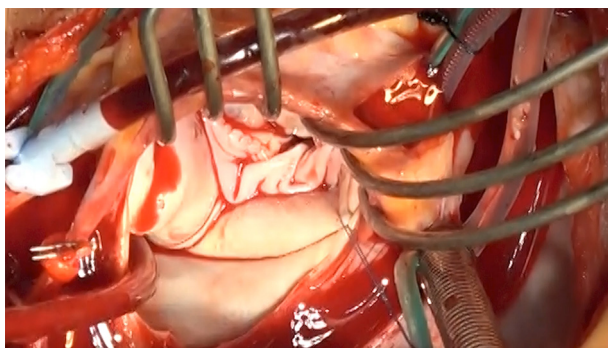
CONCLUSIONS

Leaflet expansion with autologous pericardium and sub-partial annuloplasty with PTFE reinforcement for MR in pediatric populations gives satisfactory and stable results at intermediate follow-up. We believe that the addition of a subpartial annuloplasty attenuates the risk for spinnaker phenomenon while permitting overall growth of the mitral

valve. Although we understand that these patients eventually will need subsequent surgeries, this strategy keeps them alive and well and permits normal growth.

Webcast

You can watch a Webcast of this AATS meeting presentation by going to: <https://www.aats.org/resources/leaflet-expansion-with-autologous-pericardium-and-sub-partial-annuloplasty-for-mitral-valve-repair-in-children>.



VIDEO 1. Our novel technique for mitral repair in small children and the results as well as the inferences. Video available at: [https://www.jtcvs.org/article/S2666-2507\(23\)00400-5/fulltext](https://www.jtcvs.org/article/S2666-2507(23)00400-5/fulltext).



Conflict of Interest Statement

Dr Wierup is a consultant for Medtronic, CryoLife, Edwards Lifescience, and Bristol Myers Squibb. All other authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling manuscripts for which they may have a conflict of interest. The

editors and reviewers of this article have no conflicts of interest.

References

1. Alsoufi B, Manlhiot C, McCrindle BW, Al-Halees Z, Sallehuddin A, Al-Oufi S, et al. Results after mitral valve replacement with mechanical prostheses in young children. *J Thorac Cardiovasc Surg.* 2010;39:1189-96.
2. Ibezim C, Sarvestani AL, Knight JH, Qayum O, Alshami N, Turk E, et al. Outcomes of mechanical mitral valve replacement in children. *Ann Thorac Surg.* 2019;107:143-50.
3. Beierlein W, Becker V, Yates R, Tsang V, Elliott M, de Leval M, et al. Long-term follow-up after mitral valve replacement in childhood: poor event-free survival in the young child. *Eur J Cardiothorac Surg.* 2007;31:860-5.
4. Erez E, Kanter KR, Isom E, Williams WH, Tam VK. Mitral valve replacement in children. *J Heart Valve Dis.* 2003;12:25-9.
5. Nishimura RA, Otto CM, Bonow RO, Carabello BA, Erwin JP, Guyton RA, et al. American College of Cardiology/American Heart Association task force on practice G: 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association task force on practice guidelines. *J Am Coll Cardiol.* 2014;63:57-185.
6. Chauvaud S, Jebara V, Chachques JC, el Asmar B, Mihaileanu S, Perier P, et al. Valve extension with glutaraldehyde-preserved autologous pericardium. Results in mitral valve repair. *J Thorac Cardiovasc Surg.* 1991;102:171-7.
7. Acar C, de Ibarra JS, Lansac E. Anterior leaflet augmentation with autologous pericardium for mitral repair in rheumatic valve insufficiency. *J Heart Valve Dis.* 2004;13:741-6.
8. Kehara H, Minakata K, McCarthy J, Sunagawa G, Mangukia C, Brann S, et al. Early and late results of mitral valve repair with anterior leaflet patch augmentation. *Interact Cardiovasc Thorac Surg.* 2022;35:1-9.
9. Lakew F, Sodah A, Zacher M, Batz G, Perier P, Urbanski P, et al. Augmentation of the posterior mitral leaflet in secondary mitral valve insufficiency, mid-term results. *Eur J Cardiothorac Surg.* 2022;62:ezac125.
10. Quinn RW, Wang L, Foster N, Pasrija C, Ghoreishi M, Dawood M, et al. Long-term performance of fresh autologous pericardium for mitral valve leaflet repair. *Ann Thorac Surg.* 2020;109:36-41.
11. Vida VL, Zanutto L, Carrozzini M, Padalino MA, Stellin G. Repair techniques for mitral valve insufficiency in children. *Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu.* 2018;21:41-5.

Key Words: congenital, mitral regurgitation, leaflet expansion, pediatric, neochordae