European Journal of Cardio-Thoracic Surgery 52 (2017) 1155–1160
doi:10.1093/ejcts/ezx146 Advance Access publication 23 May 2017

ORIGINAL ARTICLE

Cite this article as: Kluin J, Sojak V, Koolbergen DR, Boon R, Bökenkamp R, Hazekamp MG. Fifteen years' experience with the use of artificial chords for valve reconstruction in children. Eur J Cardiothorac Surg 2017;52:1155–60.

Fifteen years' experience with the use of artificial chords for valve reconstruction in children†

Jolanda Kluin[a,b], Vladimir Sojak[a,b], David R. Koolbergen[a,b], Rody Boon[c], Regina Bökenkamp[a] and Mark G. Hazekamp[a,b,*]

[a] Department of Cardiothoracic Surgery, Leiden University Center, Leiden, Netherlands
[b] Department of Cardiothoracic Surgery, Academic Medical Center, Amsterdam, Netherlands
[c] Department of Cardiothoracic Surgery, Isala Hospital, Zwolle, Netherlands

* Corresponding author. Department of Cardiothoracic Surgery, Leiden University Center, Albinusdreef 2, 2333 ZA Leiden, Netherlands. Tel: +31-71-5262348; e-mail; m.g.hazekamp@lumc.nl (M.G. Hazekamp).

Received 25 January 2017; received in revised form 3 April 2017; accepted 23 April 2017

Abstract

OBJECTIVES: To retrospectively review our experience with artificial chords in mitral and tricuspid reconstructive surgery in children.

METHODS: All consecutive paediatric (<18 years) patients who underwent mitral or tricuspid valve reconstruction with the use of artificial chords in our centre in the past 15 years were retrospectively analysed.

RESULTS: Thirty-nine patients (age 3 days to 17 years) underwent reconstruction of the mitral ($n = 27$) or tricuspid ($n = 12$) valve using artificial chords. Mean number of chords was 3.5 ± 1.7. In 26 of 27 mitral valve patients, chords were placed on the anterior leaflet, in one on the posterior leaflet. In 10 of the 12 tricupid valve, patients chords were placed on the anterior leaflet and in 2 on the septal leaflet. All mitral patients underwent annuloplasty (10 bilateral Wooler–Kay and 17 rigid ring annuloplasty). Ten of the 12 tricuspid patients underwent annuloplasty (1 rigid ring and 9 commissural plication). Follow-up was after 8.7 ± 5.5 years. There was no early or late mortality. The actuarial freedom from reoperation rates at 1, 5 and 10 years were 95%, 91% and 81%, respectively. No reoperations occurred in the tricuspid group. In the mitral group, there were 2 early failures and 3 late reoperations due to mitral stenosis. Restricted leaflet motion probably caused by the artificial chords was seen in only 1 patient.

CONCLUSIONS: Our data show that long-term durability of mitral and tricuspid valve reconstruction using artificial chords in children is good. Despite patient growth, restricted leaflet motion by the artificial chords does not seem to form a major problem.

Keywords: Mitral valve repair • Tricuspid valve repair • Artificial chordae • Congenital • Children • Paediatric

INTRODUCTION

In mitral valve (MV) repair in adult patients, the use of Gore-Tex artificial chords is nowadays a widespread technique with excellent results [1]. Determination of the proper length of the neochords can be difficult, and the use of preformed fixed length chordae loops can be helpful in this regard. MV repair in children remains challenging because of the fragility of the leaflets in small children and the often complex morphology. Only a few reports, all from Asian groups, describe the use of artificial chords in MV reconstruction in children and the reports of long-term results are scarce [2–5]. Publications on artificial chords in tricuspid reconstruction only involve case reports [6–10]. We adopted artificial chordal reconstruction of both the mitral and the tricuspid valves in 2001 and have subsequently reported our mid-term experience with the use of artificial chords in 21 patients (16 after MV and 5 after tricuspid valve repair) with a mean follow-up (FU) of 2 years in 2007 [11].

Artificial chords themselves do not grow. As a result, one might expect that restricted leaflet motion might occur, especially when the artificial cords are implanted in young patients. However, restricted leaflet motion in systole has not been reported in current literature. It was postulated by the group from Osaka in Japan that, once the relationship of the valve leaflets and subvalvular apparatus is corrected by surgery, it will remain with normal proportions thereafter [4]. This mechanism should be achieved by compensatory extensive growth of the leaflet or the papillary muscle.

In the present study, we give an update of our 15 years' retrospective single-centre experience with the use of artificial chords for atrioventricular valve repair in children, with a special focus on the echocardiographic results and possible signs of restricted motion of the valve leaflets during systole.

†Presented at the 30th Annual Meeting of the European Association for Cardio-Thoracic Surgery, Barcelona, Spain, 4 October 2016.

MATERIALS AND METHODS

Our institutional review board approved this retrospective study and waived the need to obtain patient consent.

Patients

From February 2001 to March 2016, 39 patients under the age of 18 underwent mitral or tricuspid valve repair with the use of one or more artificial chords at our Centre for Congenital Heart Disease Amsterdam–Leiden (CAHAL). Perioperative and most recent outpatient visit data were compiled from chart review. Mean age of the total group was 88 ± 68 months (range 3 days to just under 17 years).

Mitral valve

Twenty-seven patients underwent reconstruction of the MV with artificial chords (Table 1). Seventeen patients were female, and mean age of operation was 101 ± 67 months (11 days to just under 17 years). Four patients were operated on in the first year of life, the youngest patient being 11 days old. In terms of known aetiology of MR, there were 2 patients with Marfan syndrome, 8 patients with rheumatic disease of the MV, 3 patients with cardiomyopathy and subsequent annular dilatation and 4 with partial atrial ventricular septal defect. Table 1 summarizes the clinical characteristics of the patients. The MV pathologic disease of each patient was classified according to the Carpentier classification [12]. Although this classification can be used very well in most adult patients, the pathology in children is sometimes a combination of 2 types. In some of our patients, there seemed to be retraction of the posterior leaflet as well as true prolapse of the anterior leaflet. These cases were categorized as type III.

Tricuspid valve

Twelve patients underwent reconstruction of the tricuspid valve with artificial chords (Table 2). Six patients were female, and mean age of operation was 58 ± 59 months (3 days–16 years). Two patients were operated on in the first year of life, the youngest patient being 3 days old. There were 2 patients with tricuspid valve endocarditis. Table 2 summarizes the clinical characteristics of the patients.

Previous and associated surgical procedures

Ten of the 27 MV patients had undergone one or more previous procedures for palliation or correction of associated cardiac anomalies: coarctectomy in 4, correction of partial atrial ventricular septal defect in 3, double-outlet right ventricle repair in 2 and arterial switch, pulmonary valvulotomy and anomalous left coronary artery origin from the pulmonary artery correction each in 1 patient. Repair of concomitant cardiac lesions at the time of MV repair was performed in 12 of 27 patients. This included tricuspid reconstruction in 4 patients; pulmonary artery reconstruction in 2; an (extended) Ross procedure in 2; and a David valve-sparing root procedure, aortic valve repair, ventricular septal defect closure and closure of an atrial septal defect type I, each in 1 patient.

Of the 12 tricuspid valve patients, 7 had undergone one or more previous cardiac procedures: double-outlet right ventricle repair and arterial switch in 2, modified Blalock–Taussig shunt in 1, ventricular septal defect closure in 1 and palliation procedures for hypoplastic left heart syndrome in 1. In only 2 patients, no additional repair of concomitant cardiac lesions at the time of tricuspid valve repair had to be performed. Concomitant surgery included pulmonary valve replacement or reconstruction in 4, atrial septal defect closure in 2, closure of an open duct, modified Blalock–Taussig shunt, ventricular septal defect closure and Fontan completion, each in 1 patient.

Table 1: Preoperative characteristics of patients who underwent mitral repair

Characteristic	Number of patients (%)
Total	27
Male sex	10 (37%)
Age at operation (months)	101 ± 67
Grade of preoperative mitral regurgitation	
Moderate	3 (11%)
Severe	24 (89%)
Previous cardiac surgery	10 (37%)
Aetiology of MR (Carpentier classification)	
Type I (normal leaflet motion, annular dilatation)	1 (4%)
Type II (leaflet prolapse)	19 (70%)
Type III (leaflet restriction and pseudoprolaps)	7 (26%)

Table 2: Preoperative characteristics of patients who underwent tricuspid repair

Characteristic	Number of patients (%)
Total	12
Male sex	6 (50%)
Age at operation (months)	58 ± 59
Grade of preoperative tricuspid regurgitation	
Mild	1 (8%)
Moderate	1 (8%)
Severe	10 (83%)
Previous cardiac surgery	7 (58%)

Surgical technique

The MV was approached through a transseptal incision in all patients. In all patients who underwent MV reconstruction with artificial chords an annuloplasty was performed (Table 3). Ten patients underwent a Wooler–Kay bilateral commissural plication annuloplasty and in 17 patients a rigid Physio mitral ring (Edwards Lifesciences, Irvine, CA, USA) was implanted (6 times a size 24, 7 times a 26, one 28, one 30 and two 34 mm rings). Mean aortic clamp time was 107 ± 45 min (44–200 min). Number of artificial chords was 3.8 ± 1.8 per patient (range 2–8). In all patients except in 1, the neochords were placed onto the anterior MV leaflet.

In 2 of the 12 patients in the tricuspid valve group, no annuloplasty was performed. In 1 patient, a rigid ring (Physio 24 mm) was implanted, and all others underwent plication of 1 or 2

commissures. Mean aortic cross-clamp time was 73 ± 39 min (range 0–110 min). Mean number of neochords was 2.8 ± 1.3 per patient. In 2 patients, the chords were placed on the septal leaflet, in all others on the anterior tricuspid valve leaflet.

We used double-armed e-polytetrafluoroethylene (PTFE) sutures (Gore-Tex, W.L. Gore and Associates, Flagstaff, AZ, USA). CV-5 sutures were used for older children, while CV-7 was typically used in smaller infants and neonates [11]. We used the technique as described by El Khoury *et al.* [13]. The e-PTFE suture is first tied to the fibrous top of the papillary muscle and then the 2 ends are fixed to the free edge of the valve leaflet in a V-shape (Fig. 1). One suture thus counts for 2 new chords. The assessment of the correct length is sometimes difficult, especially when a large proportion of the leaflet is prolapsing. For the anterior leaflet, the length of the new chord is measured by bringing the free edge to the level of the anterior annulus. Frequently, additional fine-tuning is necessary on the basis of repeated water tests.

Table 3: Operative characteristics

Operative characteristic	Number of patients (%)
Mitral valve repair	27
Annuloplasty	27 (100%)
Bilateral Wooler–Kay	10 (37%)
Rigid ring annuloplasty	17 (63%)
Aortic cross-clamp time	107 ± 45
Additional cardiac surgery	12 (44%)
Number of artificial chords	3.8 ± 1.8
Location of chords	
Anterior leaflet	26 (96%)
Posterior leaflet	1 (4%)
Tricuspid valve repair	12
Annuloplasty	10 (83%)
Commissural plication(s)	9 (75%)
Rigid ring annuloplasty	1 (8%)
Aortic cross-clamp time	73 ± 39
Additional cardiac surgery	10 (83%)
Number of artificial chords	2.8 ± 1.3
Location of chords	
Anterior leaflet	10 (83%)
Septal leaflet	2 (17%)

Echocardiography

One paediatric cardiologist (R. Bökenkamp) together with one surgeon (J.K.) reviewed all the echo Doppler studies. The degree of MV regurgitation was assessed according to Helmcke *et al.* and Wu *et al.* [14, 15]. On preoperative, perioperative and most recent echocardiograms mitral and tricuspid valve regurgitation (MR and TR) was scored as 0 to 3 (none or trivial, mild, moderate or severe). Special attention was given to any signs of systolic-restricted motion of the leaflet on which the neochords were placed.

Data analysis

Continuous variables are presented as mean ± standard deviation (ranges). Actuarial freedom from reoperation was calculated by the Kaplan–Meier method.

RESULTS

Overall outcomes

Two patients were lost to FU. One moved back to Eritrea and one to the UK. The FU course was complete in all other patients, with a median FU of 8.7 ± 5.5 years (range 0.4–14.5 years). One patient with a dilated cardiomyopathy underwent heart transplantation.

Mortality

There was no early or late mortality.

Reoperations

In the tricuspid group, there were no reoperations for recurrent tricuspid regurgitation.

In the MV repair group, 2 patients were reoperated because of recurrent mitral regurgitation, 3 because of predominantly mitral stenosis. The actuarial freedom from reoperation rates for the total group was 95%, 91%, and 81% at 1, 5 and 10 years,

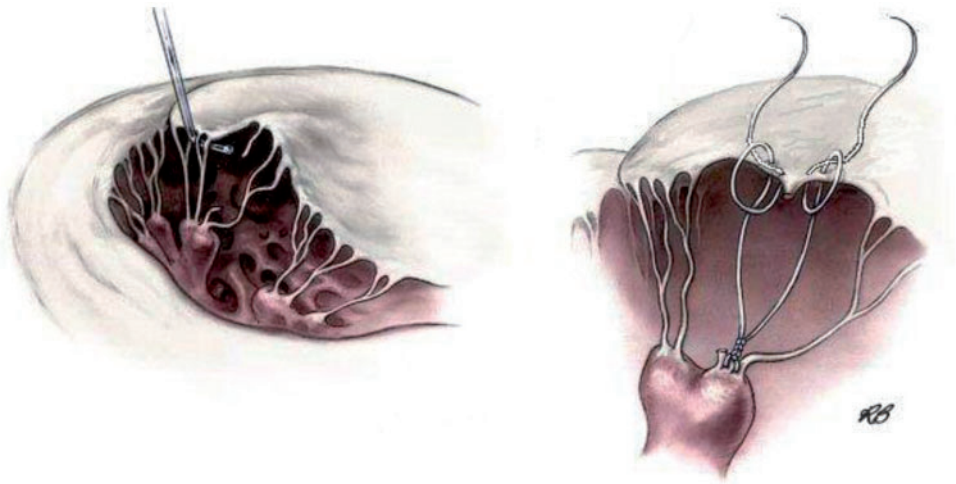


Figure 1: Operative technique of artificial chord implantation.

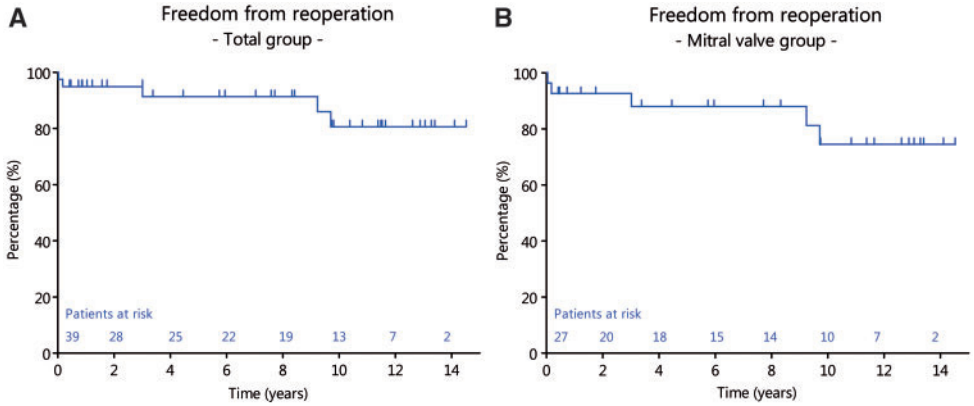


Figure 2: Kaplan–Meier curves showing actuarial freedom from reoperation rates for the total group (**A**) and for the mitral group (**B**).

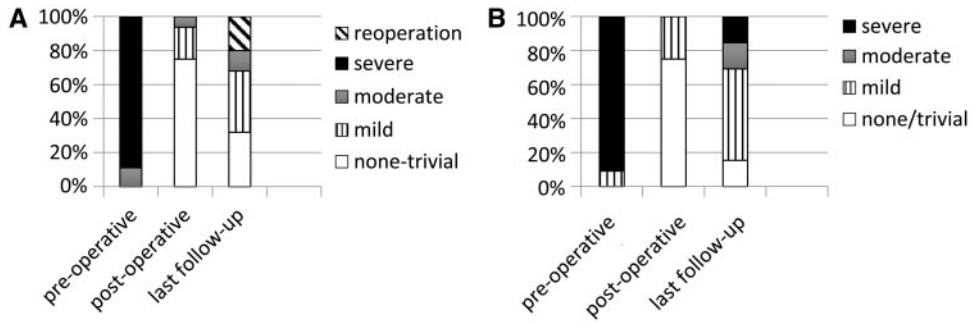
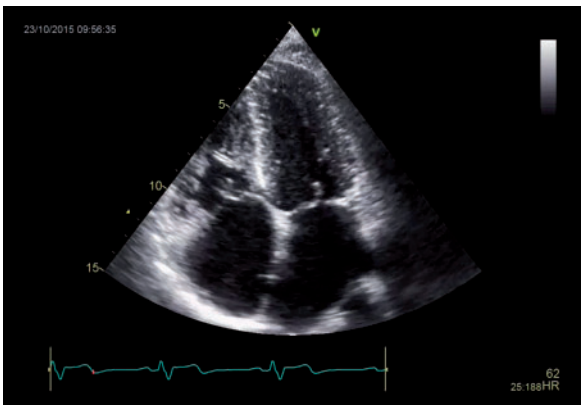


Figure 3: Echocardiographic changes in degree of regurgitation in the mitral (**A**) and tricuspid (**B**) group.

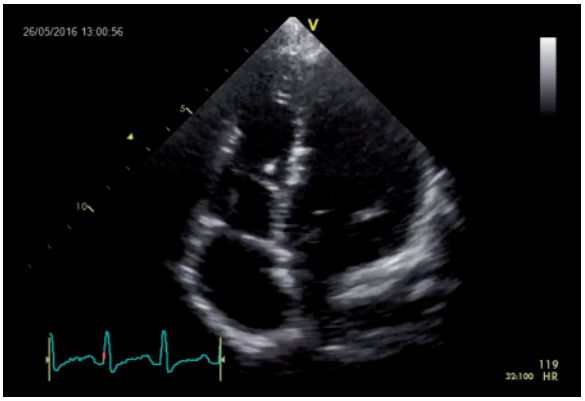
respectively (Fig. 2). The actuarial freedom from reoperation for the MV group at 1, 5 and 10 years were 93%, 88%, and 74%, respectively (Fig. 2). The 2 patients who had been operated because of recurrent mitral regurgitation were already discussed by our group in 2007 [11]. One patient was the youngest patient in the series who had been operated when he was 11 days old. He was reoperated 11 days later because of a torn commissuroplasty and received a mechanical valve (St. Jude Medical, size 17 mm). One 14-year-old boy was reoperated 2 months after the initial repair. Recurrent regurgitation was due to annuloplasty ring dehiscence and tearing of the artificial chordae from the tip of the papillary muscle. After 2007, 3 additional patients were reoperated. One 5-year-old female Marfan patient needed valve replacement 3 years after the initial repair (Physioring 26 mm, 8 neochords to the anterior mitral leaflet). There was already some restricted leaflet motion from the beginning and moderate mitral regurgitation and mitral stenosis appeared at 2 months after the initial repair. Three years later, the mitral mean gradient was 20 mmHg and the valve was replaced. The patient with rheumatic MV disease was reoperated on while she was 24 years of age. At the initial operation at 15 years of age, there was thickening and retraction of the posterior leaflet and (pseudo)prolapse of the anterior MV leaflet. Six neochords were placed to the anterior leaflet and a 26-mm ring was implanted. Because of progressive rheumatic disease and mitral stenosis, MV replacement took place 9 years after the initial repair. The fifth patient (with myocarditis) underwent mitral repair with 6 neochords to the anterior leaflet and implantation of a 24 Physio ring at the age of 16. Ten years later, he developed mitral stenosis with restricted motion and retraction of the posterior leaflet and a nicely moving anterior leaflet. On echocardiography, the turbulence was seen at the level of the ring 24. At the reoperation, the Physio ring was removed and the posterior leaflet was enlarged with a Cardiocell patch.



Video 1: Echocardiography of a patient, 14 years after mitral valve repair at the age of 7 months (bilateral Wooler–Kay commissural plication annuloplasty and 4 neochords on the anterior mitral valve leaflet). The anterior mitral leaflet shows nice unrestricted motion.

Late echocardiographic examinations

The echocardiographic changes in degree of regurgitation are shown in Fig. 3. Of the 20 patients in the mitral group who were not reoperated (5 redo MV surgery and 1 heart transplantation) and not lost to FU (1) there are 3 patients with Grade 2 regurgitation at latest FU, 9 with Grade 1 and 8 with none or trivial



Video 2: Echocardiography of a patient, 15 years after tricuspid valve repair at the age of 3 days (bilateral commissural plication and 6 neochords to the anterior tricuspid valve leaflet). The anterior tricuspid leaflet shows nice unrestricted motion.

regurgitation. The artificial chords were clearly visible on most echos. Restricted motion of the leaflet in systole due to the use of artificial chords was found in only 1 patient. This was the only patient in which neochords ($n = 6$) were placed on the posterior MV leaflet. In one other patient (4 neochords to A2–3 at the age of 71 months), there was possibly minimal restricted motion on the 4-chamber view, this however resulted in only Grade 1 MR at almost 15 years after the operation. In all other patients, no signs of restricted leaflet motion were observed on echocardiography. Even in patients who underwent neochord implantation at an early age (4 neochords to the anterior MV leaflet at 7 months), the anterior mitral leaflet had nice unrestricted motion at long-term FU (Video 1, echocardiography at the age of 14, 14 years after the repair).

In the tricuspid group, 1 patient was lost to FU. Of the remaining 11 patients, 2 have no or trivial TR, 7 have Grade 1, 1 has Grade 2 and 2 are in Grade 3 TR (Fig. 3). Restricted leaflet motion due to artificial chord implantation was not seen in any of the patients except maybe in 1 patient. This patient suffered from tricuspid valve endocarditis with ruptured chords at the age of 16. Four neochords were placed to the anterior leaflet, and the defect in the anterior leaflet was closed with a pericardial patch. Eleven years after the operation echocardiography showed a Grade 3 TR with annular dilatation and less mobility of both the anterior and the septal leaflet. Due to the mixed picture on echo and the fact that the pericardial patch might as well have led to the somewhat restricted motion of the anterior leaflet, it is unclear whether the neochords added to the TR (remember that the chords were placed at the age of 16 years). All other patients showed no restricted leaflet motion after artificial chordal implantation. Even in patients who underwent neochord implantation at an early age (6 neochords to the anterior tricuspid valve leaflet at 3 days of age), the anterior tricuspid leaflet had nice unrestricted motion at long-term FU (Video 2, echocardiography at the age of 15, 15 years after the repair). The 2 patients with Grade 3 TR at FU were the 2 patients who had no annular dilatation and did not undergo annuloplasty at the initial operation.

DISCUSSION

Heart valve replacement in children carries high mortality and morbidity rates, especially in neonates and young infants [16–19]. Therefore, even in the most difficult cases, mitral and/or tricuspid valve repair is desirable and should be attempted because it prevents the need for anticoagulation therapy and it conserves the subvalvular apparatus, ventricular geometry and ventricular function and it preserves normal heart rythm. One of the methods to increase the possibilities of valve repair is the use of artificial chords. However, the use of artificial chords in growing children is controversial for its limitation of growth in length, which may lead to restricted leaflet motion in systole. Next to our group, only 3 groups, all from Japan have reported results with artificial chord implantation in MV repair surgery in children [2, 3, 20–23]. The most recent report from the group from Osaka involves 15 children with an actuarial freedom from reoperation rates at 10 years of 65% [2]. There are 3 reports from the group from Fukuoka; the most recent report includes 78 paediatric patients [3]. Freedom from reoperation was 92.5 and 90.4% at 5 and 10 years, respectively. In both Japanese groups, Carpentier Class III mitral morphology was a risk factor for redo surgery. Both groups conclude that the use of artificial chords is safe and effective without an elevated risk of late reoperation. The group from Sendai in Japan reported the use of artificial chords in idiopathic severe mitral regurgitation due to chordal rupture, a disease that we hardly see in Western Europe [23]. All patients were aged 1–7 months. This study showed favourable results with no reoperations. Other Asian groups have reported their results on MV surgery in children as well but did not pay specific attention to the use of artificial chords. The group of Lee *et al.* from the Republic of Korea used artificial chords in 12 of the 139 patients [4]. A recent report from the group of Yakub *et al.* from Malaysia included 634 children, of which 103 had implantation of artificial chords [5]. The rate of freedom from reoperation for the entire population was 79% at 10 years. In contrast to mixed MV lesions, commissural fusion and residual mitral regurgitation (>Grade 2), the use of artificial chords was not a risk factor for reoperation. Literature on artificial chords in tricuspid valve reconstruction in children only includes case reports [6–10].

In our series, 5 patients needed mitral redo surgery. Two of them were early failures with dehiscence of the annuloplasty ring or annuloplasty sutures who had no relation to the use of artificial chords. There were 3 late reoperations. One was a Marfan patient with Carpentier type II mitral morphology. After the reconstruction with a 26 Physio ring and 8 artificial chords to the anterior MV leaflet, on echocardiography, there seemed to be some restricted motion in systole. The stenosis of the subvalvular apparatus worsened and resulted in severe MV stenosis after 3 years. In one patient, MV stenosis appeared at the level of the ring 24 with a nicely moving anterior leaflet with 6 neochords. The last redo patient had ongoing rheumatic disease and developed severe mitral stenosis 9 years after the repair. We had no reoperations in the tricuspid group, although 2 patients had Grade 3 TR at FU. Interestingly, these were the 2 patients who did not undergo annuloplasty next to the implantation of the neochords at the initial operation. Although the group is too small to draw firm conclusions, our findings suggest that it might be necessary to include annuloplasty in all patients, even in the ones that have no annular dilatation at the time of surgery.

From all our echo data, we could not find evidence of restriction of mitral or tricuspid leaflets caused by the use of artificial chords in the growing child. Even in the child in whom we implanted 4 neochords to the anterior MV leaflet at the age of 7 months, after 15 years, echocardiography showed a nicely moving anterior leaflet with only trivial mitral regurgitation. We agree

with the group of Murashita *et al.* that compensatory growth of the (anterior) leaflet or papillary muscle must take place to explain our results [2]. Apparently, once the relationship of the valve leaflets and subvalvular apparatus is corrected by surgery, it will remain with normal proportions thereafter.

The main reason for implantation of neochords is prolapse of the leaflet that cannot be treated by simpler solutions like closure of an indentation. Most of the patients had a large part of the leaflet (or the whole leaflet) prolapsing. Chordal shortening by other means (i.e. shortening the patients' own chordae or papillary muscle shortening) is (at least in our experience) much more difficult and unreliable in children than in adults. For that reason, we prefer the use of PTFE chords as their length can be accurately and reliably tailored, also in smaller children.

The mean number of chords we used changed from 4.5 in the mitral cohort in our series published in 2007 to 2.9 in the new cohort and from 4.0 to 2.3 in the tricuspid group. We think that while this can be due to coincidence, it may be true that with an increase in experience we need less PTFE chords to repair leaflet prolapse.

Study limitations

The main limitations of this study are its retrospective design and its inherent selection bias and the small numbers of patients.

CONCLUSIONS

In conclusion, reconstruction of mitral and tricuspid valve regurgitation in children can be demanding. The use of artificial chords is a tool to expand the possibilities of a successful repair. Despite patient growth, restricted leaflet motion by the artificial chords does not seem to form a major problem.

Conflict of interest: none declared.

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