Impact of reductive tricuspid ring annuloplasty on right ventricular size, geometry and strain in an ovine model of functional tricuspid regurgitation

Artur Iwasieczko a,b, Marcin Malinowski c, Monica Solarewicz a, Jared Bush a, Brian MacDougall a, Manuel Rausch d and Tomasz A. Timek a

a Division of Cardiothoracic Surgery, Spectrum Health, Michigan State College of Human Medicine, Grand Rapids, MI, USA
b Clinical Department of Cardiac Surgery, District Hospital No. 2, University of Rzeszow, Rzeszow, Poland
c Department of Cardiac Surgery, Medical University of Silesia, School of Medicine in Katowice, Katowice, Poland
d Department of Aerospace Engineering & Engineering Mechanics, Department of Biomedical Engineering, Institute of Computational Engineering and Science, University of Texas at Austin, Austin, TX, USA

* Corresponding author. Section of Cardiac Surgery, Spectrum Health, Clinical Professor of Surgery, Michigan State College of Human Medicine, 100 Michigan Avenue SE, Grand Rapids, MI 49503, USA. Tel: +16162061044; e-mail: tomasz.timek@spectrumhealth.org (T.A. Timek).

Received 20 May 2022; received in revised form 18 June 2022; accepted 1 June 2022

Abstract

OBJECTIVES: Reductive ring annuloplasty of the tricuspid annulus represents the contemporary surgical approach to functional tricuspid regurgitation (FTR). We set out to investigate the influence of moderate reductive tricuspid ring annuloplasty on tricuspid regurgitation and right ventricular (RV) size, geometry and strain in an ovine model of chronic FTR.

METHODS: Eight healthy Dorsett male sheep (62.8 ± 2 kg) underwent a left thoracotomy for placement and tightening of pulmonary artery band to at least double proximal pulmonary artery blood pressure. After 8 weeks of recovery, animals underwent sternotomy, epicardial

Presented at the 35th Annual Meeting of the European Association for Cardio-Thoracic Surgery, Barcelona, Spain, 13–16 October 2021.

© The Author(s) 2022. Published by Oxford University Press on behalf of the European Association for Cardio-Thoracic Surgery. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
INTRODUCTION

Functional tricuspid regurgitation (FTR) is commonly observed in patients with left-sided valve disease [1], and until recently, it was believed that correction of left valvular pathology would lead to resolution of tricuspid insufficiency. However, this strategy has been demonstrated to be unreliable in halting progression of tricuspid regurgitation (TR), leaving many patients with untreated significant TR [2]. Uncorrected moderate or severe TR during left heart surgery is associated with increased morbidity and mortality and is a marker of worse long-term survival regardless of left ventricular (LV) ejection fraction or pulmonary artery pressure [3]. Indeed, current cardiovascular guidelines emphasize the need for more aggressive treatment of TR [4] and the increasing incidence of TR in the community has recently been recognized as a ‘public health crisis’ [5]. FTR is primarily associated with tricuspid annular dilatation and right ventricular (RV) enlargement and dysfunction, and contemporary repair of FTR is centred on annular reduction and remodelling with prosthetic rings. However, aggressive annular reduction, as demonstrated in ovine experimental mitral annular reduction, may deleteriously affect regional myocardial performance [6]. This effect may be more pronounced on the more compliant RV myocardium. Indeed, we have recently demonstrated that progressive suture reduction of the tricuspid annulus beyond 50% of baseline area in both normal sheep [7] and those with functional FTR and biventricular failure [8], perturbed regional RV function and strain. In the current study, we set out to investigate the influence of moderate reductive tricuspid ring annuloplasty (TRA) on TR and RV size, geometry and strain in an ovine model of chronic FTR.

METHODS

Ethics statement

All animals received humane care in compliance with the Principles of Laboratory Animal Care formulated by the National Society for Medical Research and the Guide for Care and Use of Laboratory Animals prepared by the National Academy of Science and published by the National Institutes of Health. The study was approved by the West Michigan Regional Lab Institutional Animal Care and Use Committee. The approval number for the study was 2020-035.

Operative procedure

Pulmonary artery banding. Eight healthy Dorsett castrated male sheep (62 ± 2) had external left jugular intravenous catheters placed under local anaesthesia using 1% lidocaine. Animals were then anaesthetized with propofol (2-5 mg/kg intravenously), intubated and mechanically ventilated. General anaesthesia was maintained with inhalational isoflurane (1–2.5%). Fentanyl (5–20 mg/kg/min) was infused as additional maintenance of anaesthesia. Using sterile technique, the heart was exposed via limited 10 cm left thoracotomy between 4 and 5 intercostal space. Arterial 18G catheter was introduced to left internal thoracic artery for continuous arterial blood pressure measurement. Baseline epicardial echocardiography was performed to assess biventricular function and tricuspid valve competence. An umbilical tape band was placed around the distal main pulmonary trunk and progressively tightened with clips just until brink of continued haemodynamic stability as previously described [9] to at least double baseline pulmonary artery blood pressure. Proximal pulmonary artery blood pressure was continuously monitored during the procedure with a 20G intravenous catheter placed in the artery. The surgical incision was approximated in standard fashion with 2-0 suture on muscle and subcutaneous tissue, and 4-0 suture to close skin. Intercostal nerves in the region were infiltrated with 0.25% bupivacaine. The animals were taken back from the recovery room to the pen when breathing spontaneously, standing up and eating. Prophylactic antibiotics (cefazolin 2g intravenously every 12 h and gentamicin 240 mg intravenously every 24 h) were given for 10 days postoperatively beginning with the preoperative dose. The animals were followed for 8 weeks with routine clinical care including medical treatment of right heart failure as needed.

Tricuspid ring annuloplasty. After 8 weeks, the sheep were brought back to the operating room and anaesthesia was induced as described above. Using clean technique, the heart was exposed via median sternotomy and baseline epicardial echocardiographic examination was performed to assess biventricular volume, function and FTR. The animal was then fully heparinized (300 μg/kg intravenous bolus) and the right carotid artery and
The heart-lung machine was primed with Plasma-Lyte for continuous arterial blood pressure measurement. Arterial 18G catheter was introduced to left internal jugular vein were cannulated for cardiopulmonary bypass (CPB). After activated clotting time exceeded 480 s, CPB was initiated. The procedure was conducted on the beating heart. After snaring both cava, the right atrium was opened and sonomicrometry crystals (2 mm; Sonometrics Inc., London, ON, Canada) were implanted with 5-0 polypropylene suture. Six crystals were placed around the tricuspid annulus. Thirteen crystals were placed on the right ventricular free wall and tricuspid annulus area. RV volume was calculated using convex hull method based on annular and epicardial crystal coordinates.

Sonomicrometry data were acquired using a Sonometrics Digital Ultrasonic Measurement System DS3 (Sonometrics Corporation, London, ON, Canada) as previously described [10]. Data from 4 consecutive cardiac cycles during normal sinus rhythm were averaged for each animal. Data were acquired at 128 Hz with simultaneous LV pressure, RV pressure, central venous pressure and ECG recordings. All sonomicrometry recordings were analysed offline using CardioSOFT Software, ver. 3.4.82 (Sonometrics Corporation) and custom designed code for MATLAB (MathWorks, Natick, MA, USA). All parameters were calculated at end-systole and end-diastole.

End-diastole was defined as the peak of the R-wave on the ECG and end-systole as time of maximum negative dP/dt of LV pressure. RV free wall regional (basal and mid) circumferential, longitudinal and areal strains, and regional (basal, mid and lower) radius of curvature and cross-sectional area were calculated from 3D crystal coordinates as was tricuspid annulus area.

Echocardiographic data acquisition

Epicardial echocardiography was used to assess RV function and size and TR. Images were acquired with a 1.5- to 4.5-MHz transducer and Vivid S6 ultrasound machine (GE Healthcare, Chicago, IL, USA). After image acquisition, the degree of valvular insufficiency was assessed using American Society of Echocardiography criteria. The grading included comprehensive evaluation of colour flow and continuous-wave Doppler. Tricuspid regurgitation was graded accordingly and categorized by an experienced Echocardiographer as none or trace (0), mild (1), moderate (2), moderate to severe (3) and severe (4).

Statistical methods

All data are presented as mean ± standard deviation. Comparisons of parameters between Baseline and TRA were performed using Student’s t-test for dependent observations with a P-value of <0.05 considered significant. Normality was assessed by using Shapiro–Wilk test, normal distribution was confirmed, additionally, Wilcoxon test was implied for repeated measures to confirm data, with P-value of <0.05 considered as significant. Data analysis was performed using Statistical Package of Social Science (SPSS) version 26.0 for MacOS.
RESULTS

Pulmonary artery banding

Placement of the pulmonary band was associated with acute increase in systolic pulmonary artery pressure from $19.2 \pm 7.5$ to $57.4 \pm 23.1$ mmHg ($P = 0.0001$) while mean pulmonary artery pressure increased from $13.1 \pm 5.2$ to $33.8 \pm 13.5$ mmHg ($P = 0.00001$). After 8 weeks of pulmonary banding, systolic pulmonary artery pressure decreased to $41.9 \pm 6.4$ mmHg while the mean pressure decreased to $27.5 \pm 3.1$ mmHg indicative of progressive RV failure. Echocardiographic parameters acquired before application of the pulmonary artery band and after 8 weeks of banding are summarized in Table 1. Eight weeks of pulmonary banding was associated with significant TR, reduced RV function, increased wall thickness and remarkable tricuspid annulus area and left atrial dilation.

Tricuspid ring annuloplasty

Echocardiographic and haemodynamic data at Baseline following 8 weeks of pulmonary artery banding and after reductive TRA are illustrated in Table 2. TRA effectively abolished FTR without significantly affecting haemodynamics. Our echocardiographic assessment of RV function after implantation of TRA did not suggest deterioration of myocardial performance due to procedural time or prosthesis implantation. Sonomicrometry-derived tricuspid annulus area and RV geometry and size are summarized in Table 3. Implantation of the MC3 tricuspid ring resulted in significant reduction of annular area and RV volume potentially due to obliteration of tricuspid insufficiency. RV geometry, as assessed by cross-sectional area and radius of curvature was unchanged after TRA.

Right ventricular strain

RV free wall circumferential, longitudinal and areal strain in the basal and mid RV regions throughout the cardiac cycle for Baseline and after TRA is presented in Fig. 3. No change in strain patterns throughout the cardiac cycle was observed with TRA. Similarly, cardiac interventional strain at end-diastole and end-systole did not change significantly with TRA as illustrated in Fig. 4.

DISCUSSION

The current study revealed that moderate tricuspid annular reduction of 47% effectively treated experimental FTR without affecting RV shape, size or regional strain. We have previously demonstrated in healthy ovine hearts [7] that severe annular size reduction with progressive suture annuloplasty beyond 50% of initial size was associated with reduced RV function and regional strains. These initial findings were confirmed in an ovine rapid pacing model of biventricular failure and FTR [8] with annular area reduction of ~50% found optimal for control of tricuspid insufficiency and maintenance of RV function. The current data corroborate these prior studies in an isolated model of FTR and RV dysfunction using a clinically utilized annular prosthetic ring. These data may be of clinical pertinence as the concept of annular undersizing for repair of functional regurgitation first introduced by Bolling et al. [13] continues to evolve. Undersized annular reduction for repair of functional mitral regurgitation has
been shown to improve subvalvular geometry but may negatively influence regional LV myocardial performance [14].

Annular undersizing with a prosthetic ring has now been advocated for repair of FTR but aggressive annular restriction may have a greater effect on the right heart due to the more compliant nature of the RV myocardium. Clinically, use of 26 or 28 mm rings for repair of functional TR has demonstrated good immediate competency and satisfactory mid-term results [15], but only half of the studied population had severe FTR, and baseline RV anatomy achieved in our model was

Table 1: Pulmonary artery banding

| n = 8 | Pre-PB | Post-PB (8 weeks) | P-value |
|-------|--------|-------------------|---------|
| TR (+0–4) | 0.56 ± 0.53 | 3.75 ± 0.71 | 0.00002 |
| RVFAC (%) | 46 ± 20 | 38 ± 7 | 0.006 |
| TAPSE | 1.06 ± 0.44 | 0.74 ± 0.13 | 0.002 |
| RVFW thickness (mm) | 0.39 ± 0.15 | 0.56 ± 0.07 | 0.0003 |
| TA (cm) | 2.1 ± 0.8 | 3.1 ± 0.2 | 0.0000008 |
| RAA (mm²) | 6.8 ± 2.9 | 14 ± 4.2 | 0.006 |
| RA Vol (ml) | 13.9 ± 6.8 | 42.3 ± 19.7 | 0.008 |

Mean ± SD.

PB: pulmonary artery banding; RA Vol: right atrial volume; RAA: right atrial area; RVFWd: right ventricular free wall; TA: tricuspid annulus; TAPSE: tricuspid annular plane systolic excursion; TR: tricuspid regurgitation; RVFAC: right ventricular fractional change.

Table 2: Haemodynamics

| n = 8 | Baseline | TRA | P-value |
|-------|----------|-----|---------|
| TR (0–4) | 3.75 ± 0.6 | 0.3 ± 0.5 | 0.00004 |
| HR (b/min) | 106 ± 20 | 96 ± 22 | 0.3 |
| LVP (mmHg) | 87 ± 17 | 95 ± 16 | 0.1 |
| RVP (mmHg) | 42 ± 14 | 43 ± 10 | 0.5 |
| CVP (mmHg) | 12 ± 1 | 12 ± 2 | 0.9 |

Mean ± SD.

CVP: central venous pressure; HR: heart rate; LVP: left ventricular pressure; RVP: right ventricular pressure; TR: tricuspid regurgitation.

Our recent size and geometry analysis of 5 commercially available annuloplasty rings [19] revealed that size 28 mm rings have an area ranging from 462 to 538 mm² with a mean area of 492 mm². Three-dimensional echocardiography measured annular area in dilated and normal human right ventricles has been reported at 1566 and 1097 mm² [20], respectively, and as such, annular reduction with this commonly used ring size would be associated with ~68% area decrease of the annulus in a dilated right ventricle. Our prior experiments in sheep with normal hearts [7] and with RV remodelling and dysfunction implicate that such aggressive annular size reduction may have deleterious effects on RV strain patterns and performance. Furthermore, reanalysis of data from 2 large, randomized trials using under-sized ring annuloplasty to treat functional mitral regurgitation found that severe annular reduction disproportionate to ventricular cavity size was the only independent predictor of recurrent mitral insufficiency potentially due to exacerbation of subvalvular tethering [21]. Clinical [22] findings support persistent leaflet tethering after mitral annuloplasty, a mechanism that may also potentially come into play after undersized tricuspid annuloplasty. Therefore, aggressive tricuspid annular reduction may not only alter regional RV strains but also alter subvalvular geometry thus setting in motion a cycle of RV remodelling and dysfunction. As secondary TR and RV dysfunction are ‘synergistically related’ [23], these mechanisms may lead to progressive valve insufficiency.

Moderate annular reduction with prosthetic ring annuloplasty effectively treated FTR in our study but the degree of annular dilation achieved in our model was ~35% versus normal healthy sheep of similar size [24]. In a pacing model of ovine biventricular failure with TR and less pronounced annular dilation, suture annuloplasty of ~50% reduced tricuspid insufficiency but with higher grade of residual TR [8]. These experimental findings are consistent with greater efficacy of ring versus suture annuloplasty reported in clinical studies [25, 26]. However, annular dilation in patients with RV dysfunction and dilation can be very pronounced and moderate annular reduction may not suffice to achieve a competent and durable repair. Therefore, additional leaflet and subvalvular procedures may be needed to avoid ‘corking’ the annulus with severe prosthetic undersizing. Leaflet extension [27] and approximation [28] and papillary muscle approximation [29] have recently been introduced to mitigate leaflet tethering and promote valve competence. Indeed, some authors advocate that in patients with severe FTR, annular dilation over 40 mm, and leaflet tethering, a concomitant procedure should supplement annular reduction. Such a multilevel approach to the tricuspid valvular complex may permit lesser degree of annular reduction while maintaining valvular competence and avoiding exacerbation of leaflet tethering and RV dysfunction that may be induced by aggressive downsizing. With detailed knowledge prosthetic ring area and geometry and improved imaging techniques to assess annular size and RV geometry, a more customized strategy to treating FTR may replace the ‘one size fits all’ approach currently more prevalent in surgical practice.
Primary goal of valve repair for FTR is to achieve valvular competence, yet the fate of the right ventricle should not be forgotten. Therefore, it may be advantageous to maintain a balance between annular reduction and optimization of RV geometry and function which may favor subsequent reverse remodeling. Our study demonstrates that in experimental ovine FTR, 50% annular reduction with a prosthetic ring was sufficient to abolish valvular insufficiency while maintaining regional RV function. Whether more aggressive prosthetic ring undersizing in both experimental and clinical setting disturbs this balance remains to be studied.

**Limitations**

The result of the current study should be viewed in the context of several limitations. The data in the experiment were acquired in open-chest sheep under anesthesia and direct extrapolation of these results into clinical practice should be done with caution. However, annular shape and geometry have been shown to be similar in awake and anesthetized sheep [30]. Our model for functional TR was based on increased RV afterload due to pulmonary artery constriction which is distinctly different from clinical pulmonary hypertension arising from left-sided valvular lesions. We have previously used a rapid pacing biventricular failure model but feel that the current experimental preparation...
allows a more focused evaluation of tricuspid valve complex remodelling during the evolution of FTR. We assessed only epicardial strains using wired sonomicrometry crystals and no information regarding mid-wall and endocardial strains can be deemed from our study. Although the study demonstrated that moderate annular reduction did not alter RV free wall strain patterns, it is unclear whether further prosthetic undersizing would have a deleterious effect and this possibility requires further study. Experiment was performed as acute but under chronic condition, and our conclusions are limited to this setting. We have previously carried out a series of experiments investigating the influence of progressive downsizing of the tricuspid annulus with De Vega suture annuloplasty in sheep [8]. Using one size ring annuloplasty made this study clinically limited; however, future studies with higher range of ring size may be required to confirm our findings. Two CPBs are also very pertinent and are certainly a limitation of the study. However, both procedures (sonomicrometry implantation and ring annuloplasty) were performed with heart beating to minimize the effect on myocardial function. Furthermore, each animal served as its own control to add power to the statistical conclusion of the study.

Funding
This study was founded by internal grant from Meijer Heart and Vascular Institute at Spectrum Health.

Conflict of interest: Artur Iwasieczko and Marcin Malinowski were Peter C. and Pat Cook Research Fellows in Cardiothoracic surgery. No conflict of interest to declare.

Data availability
Raw data were generated at Spectrum Health research office. All relevant data are within the manuscript and its supporting files. The data that support the findings of this study are available on request from the corresponding author.

Author contributions
Artur Iwasieczko: Formal analysis; Investigation; Methodology; Supervision; Writing—original draft. Monica Solarewicz: Investigation. Marcin Malinowski: Formal analysis; Methodology; Jared Bush: Investigation; Methodology. Brian MacDougall: Investigation; Methodology. Manuel Rausch: Data curation; Formal analysis; Software; Validation. Tomasz A. Timek: Investigation; Project administration; Supervision; Writing—review & editing.

Reviewer information
Interactive CardioVascular and Thoracic Surgery thanks Omar A. Jarral, Roman Gottardi and the other anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES
[1] Shiran A, Sagie A. Tricuspid regurgitation in mitral valve disease incidence, prognostic implications, mechanism, and management. J Am Coll Cardiol 2009;53:401–408. https://doi.org/10.1016/j.jacc.2008.09.048.
[2] de Bonis M, Lapenna E, Pozzoli A, Nisi T, Giacomini A, Calabrese M et al. Mitral valve repair without repair of moderate tricuspid regurgitation. Ann Thorac Surg 2015;100:2206–2212. https://doi.org/10.1016/j.athoracsur.2015.05.108.
[3] Dreyfus GD, Corbi PJ, Chan KMJ, Bahrami T. Secondary tricuspid regurgitation or dilatation: which should be the criteria for surgical repair? Ann Thorac Surg 2005;79:127–132. https://doi.org/10.1016/j.athoracsur.2004.06.057.
[4] Otto CM, Nishimura RA, Bonow RO, Carabello BA, Erwin JP, Gentile F et al. 2020 ACC/AHA guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation 2021;143:e5–e71. https://doi.org/10.1161/CIR.0000000000000932.
[5] Enriquez-Sarano M, Messika-Zeitoun D, Topilsky Y, Tribouilloy C, Benfari G, Michelena H. Tricuspid regurgitation is a public health crisis. Prog Cardiovasc Dis 2019;62:447–51.
[6] Cheng A, Nguyen TC, Malinowski M, Liang D, Daughters GT, Ingels NB et al. Undersized mitral annuloplasty inhibits left ventricular basal wall thickening but does not affect equatorial wall cardiac strains. J Heart Valve Dis 2007;16:349–358.
[7] Malinowski M, Jazwiec T, Goehler M, Bush J, Quay N, Ferguson H et al. Impact of tricuspid annular size reduction on right ventricular function, geometry and strain. Eur J Cardiothorac Surg 2019;56:400–8.
[8] Jazwiec T, Malinowski M, Ferguson H, Wodarek J, Quay N, Bush J et al. Effect of variable annular reduction on functional tricuspid regurgitation and right ventricular dynamics in an ovine model of tachycardia-induced cardiomyopathy. J Thorac Cardiovasc Surg 2021;161: e277–e286. https://doi.org/10.1016/j.jtcvs.2019.10.194.
[9] Verbelen T, Claus P, Burkhoff D, Driessen RB, Kadur Nagaraju C, Verbeke E et al. Low-flow support of the chronic pressure-overloaded right ventricle induces reversed remodeling. J Heart Lung Transplant 2018;37:151–160. https://doi.org/10.1016/j.healun.2017.09.014.
[10] Malinowski M, Wilton P, Khaghani A, Langholz D, Hooker V, Eberhart L et al. The effect of pulmonary hypertension on ovine tricuspid annular dynamics. Eur J Cardiothorac Surg 2016;49:40–5.
[11] Meador WD, Malinowski M, Jazwiec T, Goehler M, Quay N, Timek TA et al. A fiduciary marker-based framework to assess heterogeneity and anisotropy of right ventricular epicardial strains in the beating ovine heart. J Biomech 2018;80:179–185. https://doi.org/10.1016/j.jbiomech.2018.08.036.
[12] Goktepe S, Bothe W, Kvitting J-P, Swanson JC, Ingels NB, Miller DC et al. Anterior mitral leaflet curvature in the beating ovine heart: a case study using videofluoroscopic markers and subdivision surfaces. Biomech Model Mechanobiol 2010;9:281–93.
[13] Bolling SF, Deeb GM, Brusting LA, Bach DS. Early outcome of mitral valve reconstruction in patients with end-stage cardiomyopathy. J Thorac Cardiovasc Surg 1995;109:676–82. https://doi.org/10.1016/S0022-5223(95)70348-9.
[14] Cheng A, Nguyen TC, Malinowski M, Liang D, Daughters GT, Ingels NB et al. Effects of undersized mitral annuloplasty on regional transmural left ventricular wall strains and wall thickening mechanisms. Circulation 2006;114(Suppl)I:1600–9. https://doi.org/10.1161/CIRCULATIONAHA.105.001529.
[15] Maghami S, Ghoresi M, Foster N, Dawood MY, Hobbs GR, Stafford P et al. Undersized rigid nonplanar annuloplasty: the key to effective and durable repair of functional tricuspid regurgitation. Ann Thorac Surg 2016;102:735–42.
[16] Calafiore AM, Foschi M, Kheirallah H, Alsaied MM, Alfonso JJ, Tancredi F et al. Early failure of tricuspid annuloplasty. Should we repair the tricuspid valve at an earlier stage? The role of right ventricle and tricuspid apparatus. J Card Surg 2019;34:404–11.
[17] Navia JL, Nowicki ER, Blackstone EH, Brozzi NA, Nento DE, Atik FA et al. Surgical management of secondary tricuspid valve regurgitation: annulus, commissures, or leaflet procedure? J Thorac Cardiovasc Surg 2010;139:1473–1482.e5. https://doi.org/10.1016/j.jtcvs.2010.02.046.
[18] Pahwa S, Saran N, Pochettino A, Schaff H, Stulak J, Greason K et al. Outcomes of tricuspid valve surgery in patients with functional tricuspid regurgitation. Eur J Cardiothorac Surg 2019;55:577–585. https://doi.org/10.1016/j.ejcts.2019.06.010.350.
[19] Mathur M, Malinowski M, Timek TA, Rausch MK. Tricuspid annuloplasty rings: a quantitative comparison of size, nonplanar shape, and stiffness. Ann Thorac Surg 2020;100:1605–14.
[20] Ring L, Rana BS, Kydd A, Boyd J, Parker K, Rusk RA. Dynamics of the tricuspid valve annulus in normal and dilated right hearts: a three-
dimensional transoesophageal echocardiography study. Eur Heart J Cardiovasc Imaging 2012;13:756–62. https://doi.org/10.1093/ehjci/jes040.

[21] Capoulade R, Zeng X, Overbey JR, Ailawadi G, Alexander JH, Ascheim D et al. Impact of left ventricular to mitral valve ring mismatch on recurrent ischemic mitral regurgitation after ring annuloplasty. Circulation 2016;134:1247–56.

[22] Hung J, Papakostas L, Tahta SA, Hardy BG, Bollen BA, Duran CM et al. Mechanism of recurrent ischemic mitral regurgitation after annuloplasty: continued LV remodeling as a moving target. Circulation 2004; 110(11 Suppl 1):I85–90. https://doi.org/10.1161/01.CIR.0000138192.65015.45.

[23] Vargas Abello LM, Klein AL, Marwick TH, Nowicki ER, Rajeswaran J, Puwanant S et al. Understanding right ventricular dysfunction and functional tricuspid regurgitation accompanying mitral valve disease. J Thorac Cardiovasc Surg 2013;145:1234–1241. https://doi.org/10.1016/j.jtcvs.2012.01.088.

[24] Jazwiec T, Malinowski M, Bush J, Goehler M, Quay N, Parker J et al. Right ventricular free wall stress after tricuspid valve annuloplasty in acute ovine right heart failure. J Thorac Cardiovasc Surg 2019;158:759–768. https://doi.org/10.1016/j.jtcvs.2018.11.092.

[25] Sohn SH, Kim KH, Lee Y, Choi JW, Hwang HY. Long-term outcomes of rigid ring versus De Vega annuloplasty for functional tricuspid regurgitation: a propensity score-matching analysis. J Thorac Cardiovasc Surg 2021;161:1788–1798. https://doi.org/10.1016/j.jtcs.2019.11.049.

[26] Charfeddine S, Hammami R, Trki F, Abid L, Hentati M, Frkha I et al. Plastic repair of tricuspid valve: Carpentier’s ring annuloplasty versus De VEGA technique. Pan Afr Med J 2017;27:119.

[27] Pettinari M, Bertrand P, van Kerrebroeck C, Vandervoort P, Gutermann H, Dion R. Mid-term results of leaflet augmentation in severe tricuspid functional tethering. Eur J Cardiothorac Surg 2016;50:504–8.

[28] de Bonis M, Lapenna E, Barili F, Nisi T, Calabrese M, Pappalardo F et al. Long-term results of mitral repair in patients with severe left ventricular dysfunction and secondary mitral regurgitation: does the technique matter? Eur J Cardiothorac Surg 2016;50:882–9.

[29] Matsumiya G, Kohno H, Matsuura K, Sakata T, Tamura Y, Watanabe M et al. Right ventricular papillary muscle approximation for functional tricuspid regurgitation associated with severe leaflet tethering. Interact CardioVasc Thorac Surg 2018;26:700–2.

[30] Jazwiec T, Malinowski M, Proudfoot AG, Eberhart L, Langholz D, Schubert H et al. Tricuspid valvular dynamics and 3-dimensional geometry in awake and anesthetized sheep. J Thorac Cardiovasc Surg 2018;156:1503–11.