Uncertainties and challenges in surgical and transcatheter tricuspid valve therapy: a state-of-the-art expert review

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ABSTRACT

Tricuspid regurgitation (TR) is a frequent and complex problem, commonly combined with left-sided heart disease, such as mitral regurgitation. Significant TR is associated with increased mortality if left untreated or recurrent after therapy. Tricuspid regurgitation was historically often disregarded and remained undertreated. Surgery is currently the only Class I Guideline recommended therapy for TR, in the form of annuloplasty, leaflet repair, or valve replacement. As growing experience of transcatheter therapy in structural heart disease, many dedicated transcatheter tricuspid repair or replacement devices, which mimic well-established surgical techniques, are currently under development. Nevertheless, many aspects of TR are little understood, including the disease process, surgical or interventional risk stratification, and predictors of successful therapy. The optimal treatment timing and the choice of proper surgical or interventional technique for significant TR remain to be elucidated. In this context, we aim to highlight the current evidence, underline major controversial issues in this field and present a future roadmap for TR therapy.

INTRODUCTION

Tricuspid regurgitation (TR) is commonly detected on echocardiography.[1] Moderate/severe TR is associated with an increased risk for cardiac and all-cause mortality.[2,3] A recent meta-analysis demonstrated that moderate/severe TR is associated with a two-fold increased mortality risk compared with no/mild TR, which seems to be independent of pulmonary pressures and right heart failure (HF).[4] Topilsky et al.[5] reported that quantitative measures of TR were associated with increased mortality in patients with left ventricular (LV) systolic dysfunction. These evidences may push towards an earlier indication of correction of TR.

Tricuspid regurgitation remains undertreated as a result of our limited understanding of the disease and how to quantify it.[6–8] Surgery is currently the only Class I Guideline Recommended therapy for TR,[9,10] which is most often performed during left-sided heart surgery. Previous estimates indicate that <1% of patients undergo tricuspid valve (TV) surgery.[11] The operative mortality of isolated TV surgery could be high due to the late referral, multiple comorbidities, and right ventricle (RV) remodelling.[12,13] Due to the paucity of evidence, American and European guideline recommendations for the management of TR are limited, and the timing for surgical intervention is still debated.[9,10] As the management of valvular heart disease moves towards less invasive surgical and transcatheter therapies, several techniques and devices are applied to the TV.[14,15] Nevertheless, many aspects of TR are little understood. In this context, we aim to highlight controversial issues and present a future roadmap for TR therapy.

PATHOPHYSIOLOGY OF TRICUSPID REGURGITATION AND RATIONALE FOR THERAPY

With the growing incidence of atrial fibrillation,[16] the use of intracardiac devices,[17] and the global epidemic of valvular heart disease, the prevalence of TR is likely to increase.[18] Recently, Topilsky et al.[19] reported the prevalence of TR (0.55%) in a community setting which was about one-fourth of all left-sided valve disease and similar to the prevalence of aortic stenosis. The distribution pattern of TR was primary in 14.6% and secondary in 85.4% of patients.[19] Primary TR results from primary abnormalities of the TV apparatus and can be divided into congenital and acquired disease. The latter may include rheumatic disease, carcinoid disease, infective endocarditis, degenerative, or iatrogenic disease from implantable device lead-induced TV injury/dysfunction or RV endomyocardial biopsy.[20] Secondary TR is due to annular dilatation (with or without leaflet tethering) or RV dilatation (typically associated with leaflet tethering), with left-sided heart disease and/or pulmonary hypertension being the most frequent aetiologies.[20,21] The disease process of TR is not fully understood and is likely influenced by the underlying aetiology, concomitant heart disease, and haemodynamic abnormalities.[22] Age,

presence of device leads, mild TR at baseline, and receiving left-sided valvular surgery (without concomitant TV surgery) have been shown as predictors of development of significant TR.[23]

Currently, long-term data on the beneficial effect of isolated surgical TV therapy compared to medical therapy remains scarce.[24] According to data from theNational Inpatient Sample files from 2004 to 2013 in the USA, isolated TV surgery was performed in 15% of all patients who underwent TV surgery, with high in-hospital mortality rate (8–10%) that has remained unchanged over the 10-year period.[12,13] This suboptimal outcome is likely related to comorbidities and referral timing rather than to the risk of isolated TV surgery.[25,26] Furthermore, residual or late significant TR after mitral valve replacement is independently associated with poor outcome.[27] Adding TV repair during left-sided heart surgery did not increase surgical risk and could result in reverse RV remodelling with reduction of symptoms.[28–30] Therefore, a more aggressive approach to correct concomitant TR in the presence of annular dilatation may reduce the chance of late TR progression after left-sided valve surgery.

SPECIFIC ANATOMICAL CONSIDERATIONS INTERFERING WITH TRICUSPID VALVE

The TV is a complex apparatus consisting of leaflets, tricuspid annulus, tendinous cords, papillary muscles, and the associated RV. The normal tricuspid annulus is a saddle-shaped ellipsoid surrounded by several critical anatomical structures, including the atrioventricular node, right coronary artery, coronary sinus ostium, and non-coronary sinus of Valsalva (Figure 1A). Multiple TV structural abnormalities may be encountered as a result of different aetiologies with various morphological changes. Tricuspid annulus dilation, right atrium/RV dilation, and leaflet malcoaptation are the most common changes in secondary TR.When tricuspid annulus dilation occurs, its shape becomes more circular and planar (Figure 1B).[31,32] It is usually observed in the anatomical location of anterolateral free wall and posterior border. Leafletmalcoaptation may occur due to inadequate leaflet length to cover the dilated annulus, or in the absence of adequate chordal redundancy resulting in leaflet tethering. The region of malcoaptation occurs often centrally or extends from the anteroseptal commissure towards the posteroseptal commissure.[32,33]

GUIDELINE RECOMMENDATIONS FOR TRICUSPID REGURGITATION THERAPY

Tricuspid regurgitation often presents as a component of a complex heart disease and its clinical manifestations range from subtle symptoms to advanced HF with multiorgan involvement. At the far end of the disease spectrum, there may be a point of no return where irreversible

RV dysfunction persists regardless of therapy. Therefore, a timely therapy is essential to avoid worsening of causative pathology and the onset of complications caused by TR. However, the indication and optimal timing of surgery remain controversial due to insufficient evidence.

The comparison of the American[32] and the European guidelines[9] for the management of TR is provided in the Supplementary material online, Table S1. In both guidelines, most of the Classes I and IIa indications for intervening on significant TR require concomitant leftsided valve surgery. Isolated TV surgery is recommended in patients with severe TR who are either symptomatic or are developing progressive RV dilatation/dysfunction.[9] Nevertheless, patients with severe TR are often asymptomatic for a long period of time and symptoms are not specific, contributing to late referral for surgery.[34] Recently, an extended five-stage classification of secondary TR was proposed to help categorize the severity of disease presenting late in the disease process.[15] Symptoms, severity of TR, leaflet coaptation, tethering, annular remodelling, and RV function need to be evaluated to determine the timing and options of treatment.

On the other hand, the 'optimal medical treatment' has not yet been defined for right-sided HF. Recently, the American Heart Association released a scientific statement on evaluation and management of right-sided HF.[35] Based on the document, medical treatment of right-sided HF should focus on volume management (diuretics and renal replacement therapies), afterload reduction (pulmonary vasodilators) and, if needed, mechanical circulatory support.

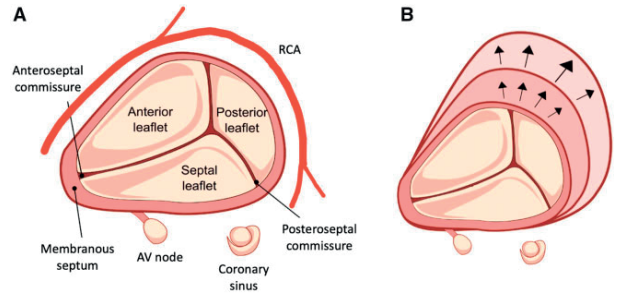


Figure 1. Anatomical structure of the tricuspid valve. (A) Normal and (B) dilated tricuspid annulus.

RISK STRATIFICATION AND HEART TEAM DECISION-MAKING

In the past decades several models were developed to predict outcome in cardiac surgery.[36] Nevertheless, until recently, no specific risk model addressed isolated TV surgery. LaPar et al.[37] used the Society of Thoracic Surgeons (STS) database to develop a risk score for patients undergoing TV surgery. They included age, sex, stroke, haemodialysis, LV ejection fraction, chronic lung disease, New York Heart Association functional class, reoperation, and operative characteristics in their models. Although the authors developed well-discriminated and calibrated models, they could not include indices of RV dysfunction and liver dysfunction, because these

data were simply not collected. Testing these models will require large clinical datasets, however, datasets like the STS database are currently designed for the majority of patients (with left-sided valve surgery) and do not specifically address the right heart.[38] Therefore, we propose a standardized approach and risk stratification process for heart team decision-making. Our proposed stepwise assessment is as follows (Take home figure):

Step 1: Patient demographics (age and sex).

Step 2: Clinical symptoms (New York Heart Association functional class).

Step 3: Comorbidities [stroke, major organ dysfunction (lung, kidney, and liver)].

Step 4: Cardiac pathological remodelling (TR severity, local remodelling of TV, RV remodelling, pulmonary vascular resistance, and left-sided heart disease).

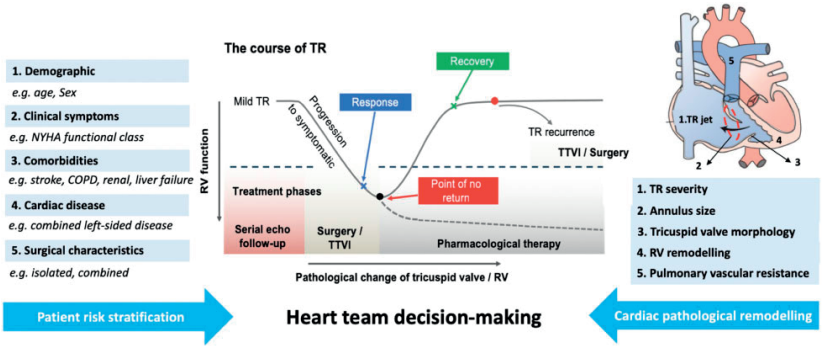
Step 5: Surgical or interventional characteristics (isolated, combined, elective, or emergent).

Step 6: Combining 3R's (Risk, Reversibility, and Recurrence) information to allocate patient profiles.

Step 7: Decision-making by the multidisciplinary heart team to provide appropriate treatment (surgical, minimal invasive surgical, transcatheter, pharmacological, or palliative).

IMAGING ASSESSMENT FOR TRICUSPID REGURGITATION TREATMENT

Imaging assessment for TR treatment runs in three phases: (i) patient assessment for decision-making; (ii) peri-operative/peri-interventional planning and guidance; and (iii) assessing therapeutic efficacy and durability during follow-up.



Take home figure. Heart team decision-making for treatment of tricuspid regurgitation. COPD, chronic obstructive pulmonary disease; NYHA, New York Heart Association; RV, right ventricle; TR, tricuspid regurgitation; TTVI, transcatheter tricuspid valve intervention.

Imaging for decision-making in patients with tricuspid regurgitation

A stepwise approach using multimodality imaging to assessment of TR is shown in Table 1. First, determining the presence of TR, as well as the TV morphology and aetiology. Second is to evaluate TR severity. Third is to assess the haemodynamic impact in terms of regurgitant volume and coexisting pressure overload. Fourth is to identify the presence (and severity) of associated left-sided heart disease. Finally, to assess the presence (and severity) of RV remodelling. Two-dimensional echocardiography, including tissue Doppler imaging and RV strain, is currently the most widely used imaging modality (Table 2). Three-dimensional techniques such as three-dimensional echocardiography, cardiovascular magnetic resonance, or multislice computed tomography are powerful tools for assessing the TV annulus, as well as the RV and LV size and global function.[39]

The current echocardiographic criteria for grading TR only consider three grades of severity: mild, moderate, and severe.[40] In the SCOUT trial,[41] despite the severity of TR reduced from 'severe' to 'severe', the equivalent quantitative reduction of a 'grade' of TR was associated with an increase in stroke volume and improved quality of life. Therefore, an extended five-grade scale of 'mild, moderate, severe, massive, and torrential' has been proposed to accommodate

Table 1. Five-stepwise approach for evaluations of patients with suspected or established tricuspid regurgitation

Target	Imaging modalities needed to evaluate
Tricuspid valve morphology (TV annulus dilatation and leaflet tethering)	TTE and TOE (2DE and 3DE)
TR severity	2DE/3DE with Doppler, CMR if unclear
Haemodynamic impact	2DE with Doppler
Preload (RV filling)	2DE and M-mode for longitudinal function
Afterload (pulmonary atrial pressure and pulmonary vascular resistance) RV size and function	3DE for RV volumes
Left-sided heart disease	2DE/3DE
Right heart remodelling and function	Ideally 3D modality for RV size and function CMR or 4D MSCT or 3DE > 2DE 3DE >> 2DE For preclinical studies and first-in-man studies or small efficacy studies, CMR and 4D CT may be appropriate. For Large studies and routine care, 3DE is good alternative

2DE, two-dimensional echocardiography; 3DE, three-dimensional echocardiog-raphy; CMR, cardiovascular magnetic resonance; MSCT, multislice computed tomography; RV, right ventricle; TOE, transoesophageal echocardiography; TR, tricuspid regurgitation; TTE, transthoracic echocardiogram.

the large variability amongst patients with severe TR.[42] Moreover, recent publications have shown that the current cut-off values for quantitative parameters used to assess TR severity are inadequate to quantify the burden on the RV and it is likely that lower threshold values of

effective regurgitant orifice area (EROA) and regurgitant volume define severe TR.[43] This finding was also supported by the study of Bartko et al.[44] showing a significant increase in mortality and morbidity for EROA ≥0.2 cm^2 and regurgitant volume ≥20mL in HF patients with reduced ejection fraction. This may potentially impact the therapeutic decision-making, particularly timing for intervention.

Table 2. Advantages and limitations of imaging modalities in TR assessment

Imaging technique	Main advantages	Main limitations
2DE	Real-time, versatile, high frame rate	Insufficient for 3D complex structures such as TV annulus, LV, and RV size and function
3DE	Both simultaneous multi-plane imaging and real-time 3D imaging. 3DE is an excellent tool for quantification of ventricular volume and function	Lower frame rate than in 2DE, currently less spatial resolution compared to 2DE, inability to assess tissue characterization such as calcifications or fibrosis
TOE (2DE and 3DE)	Real-time intra-procedural planning and guidance	Four levels of imaging allow a comprehensive evaluation of the valve: mid-oesophageal, deep-oesophageal, transgastric, and deep-transgastric
CMR	TV severity, perfusion, fibrosis, tissue characterization, and chamber quantification	Less versatile
MSCT	Superb resolution, calcification, excellent tool for TV annulus and preplanning, best to assess radiopaque surgical, and percutaneous implants	Radiation and less versatile

2DE, two-dimensional echocardiography; 3DE, three-dimensional echocardiography; CMR, cardiovascular magnetic resonance; LV, left ventricle; MSCT, multislice computed tomography; RV, right ventricle; TOE, transoesophageal echocardiography; TV, tricuspid valve.

Imaging for peri-operative/peri-interventional planning and guidance

Transthoracic echocardiography (TTE) supported by transoesophageal echocardiography (TOE) is the main tool for preplanning. For transcatheter therapy targeting the leaflets such as edge-to-edge repair, TOE, particularly using transgastric views is essential for assessment of leaflet morphology, coaptation gap, device landing zones and location of main TR jet. Transoesophageal echocardiography guides procedural planning and allows for outcome prediction.[45] For annuloplasty devices, intracardiac echocardiography may be an alternative,[46] especially when TOE images are suboptimal.

Multislice computed tomography could aid in TV preplanning for transcatheter therapies mimicking surgical annuloplasty, spacer devices, and transcatheter TV replacement.[47] It allows for accurate measurement of the TV annulus, device landing zone, relationship between the annulus and right coronary artery, annular tissue quantity and quality, and access selection and guidance.[48]

Imaging of therapeutic efficacy and durability

Surgical success of TV repair is defined, by imaging in the immediate post-operative period as reduction in TR severity to mild or less and reduction of TV annulus diameter. In the long run, reverse RV remodelling, if present, as well as reduction of the RV afterload, are important imaging endpoints. These are correlated to patients' symptomatic and functional improvement. In contrast, the need for reintervention or mortality is the main clinical endpoints reflecting failure of repair. Ideally, the imaging results of successful transcatheter repair should match those of surgical repair. However, most candidates for transcatheter TV repair are currently patients with advanced RV dysfunction and are often beyond the point of complete repair.

TRICUSPID REGURGITATION THERAPY—SURGICAL PERSPECTIVE

Tricuspid valve repair (annulus, leaflets, and sub-valvular apparatus)

In the setting of secondary TR with primarily annular dilation, a reduction annuloplasty is the most commonly used surgical approach. Now, almost abandoned, the first suture annuloplasty was described by Kay et al.[49] This 'bicuspidization' technique is done by tightening a suture from the anteroposterior commissure to the posteroseptal commissure (Figure 2).[49] The second technique was described by De Vega et al.[50] It consists of two parallel lines of running sutures starting at the posteroseptal commissure at the annulus level. The suture follows the annulus with a stitch approximately every 5mm to the fibrous trigone. Thereafter, a pledget is placed and the suture is reversed.[50] Nowadays, TV annuloplasty using a rigid ring is the most often applied technique, which provides a lower recurrent rate of significant TR compared to suture or flexible ring annuloplasty.[51,52] However, the use of a rigid ring was associated with an increased risk of early ring dehiscence.[53] Ideally, a ring annuloplasty should meet the following criteria: (i) restoring the three-dimensional shape of the annulus to reduce leaflet stress and tethering; (ii) addressing the remodelling along the RV free wall and also be 'open' at the septal leaflet sector to protect the conduction system; and (iii) being flexible to maintain annular dynamicity and prevent ring dehiscence.[54,55]

In case of severe leaflet tethering, an annuloplasty alone is usually not sufficient to ensure adequate repair.[56] Dreyfus et al.[57] described an anterior leaflet augmentation technique to address the tethering. An edge-to-edge technique similar to the Alfieri stitch in mitral valve repair has been performed resulting in a triple 'clover-like' orifice.[58] In addition, several case reports exist on neochordae repair of the TV.[59,60] Various other repair techniques specifically addressing a primary cause (e.g. Ebstein anomaly or endocarditis) are reported in literature.[61,62]

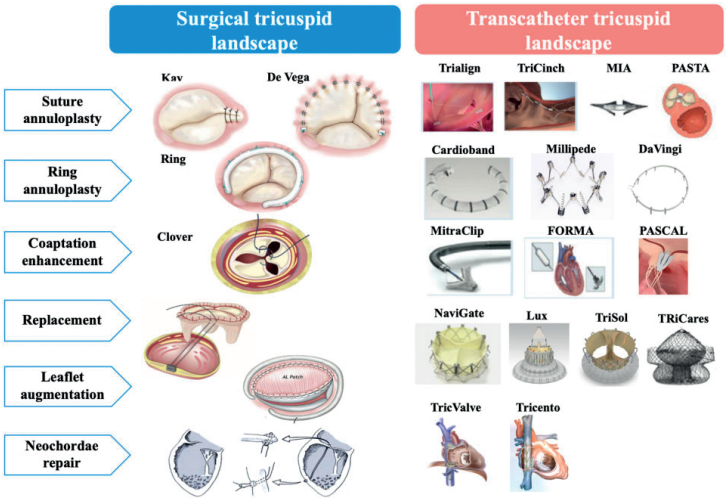


Figure 2. Surgical and transcatheter treatments for tricuspid regurgitation. Direct suture annuloplasty: Trialign™ (Mitralign Inc., Tewksbury, MA, USA), TriCinch™ (4Tech Cardio Ltd., Galway, Ireland), MIA™ (Micro Interventional Devices Inc., Newtown, PA, USA), pledget-assisted suture tricuspid valve annuloplasty (PASTA). Ring annuloplasty: Cardioband (Edwards Lifesciences, Irvine, CA, USA), IRIS (Millipede Inc., Santa Rosa, CA, USA), DaVingi (Cardiac Implants Ltd, Israel). Coaptation enhancement: edge-to-edge with MitraClip® (Abbott Vascular, Santa Clara, CA, USA), PASCAL (Edwards Lifesciences), FORMA (Edwards Lifesciences). Valve replacement: NaviGate (NaviGate Cardiac Structures, Inc., Lake Forest, CA, USA), Lux (Ningbo Jenscare Biotechnology Co., Ltd., Ningbo, China), Trisol (Trisol Medical, Haifa, Israel), TRiCares (TRiCares SAS, Paris, France), TricValve® (P&F Products & Features GmbH, Vienna, Austria), Tricento® (NVT GmbH, Hechingen, Germany and NVT AG, Muri, Switzerland).

Tricuspid valve replacement

Tricuspid valve replacement is usually reserved for patients with primary TV disease. Nevertheless, the latest consensus is that patients with severe RV dysfunction, very large annulus, or severe tethering may be better served with TV replacement.[63] A recent meta-analysis showed comparable outcomes in terms of survival, reoperation, and prosthetic valve failure after TV replacement between biological and mechanical valves. Nonetheless, mechanical prostheses had a higher risk of thrombosis.[64] These results were derived from observational and retrospective studies. Randomized studies are needed to determine which type of valve is better for TV replacement. Currently, biological prostheses are preferred and offer an option for future transcatheter valve-in-valve implantation.

Surgical controversies

The best timing of surgery in patients with TR remains in question. Repairing the TV in patients with a dilated tricuspid annulus (intraoperative ≥70mm, TTE ≥40mm) without significant TR during left-sided heart surgery has been debated[65] since 2005 when this concept was initially presented by Dreyfus et al.[28] This debate is partly fuelled by the lack of evidence for the validity of the conversion of 70mm as measured intraoperatively to 40mm on TTE.[66] Furthermore, since the TV annulus is not planar, even small variations in the ultrasound beam plane may result in

substantial differences in the measurement.[67] The question as to whether repairing a TV with dilated annulus in patients with trace or mild TR at the time of planned mitral valve surgery could improve clinical outcomes will be explored in an ongoing randomized trial (ClinicalTrials.gov identifier: NCT02675244).

As for patients with late or recurrent significant TR after previous left-sided surgery, current guidelines consider this is a Class IIa indication for TV surgery. Yet it has been shown that reoperation on the TV may be associated with a high mortality.[68,69] In combination with multiple co-existing comorbidities or old age, many surgeons are reluctant to operate on these patients, especially if pulmonary hypertension or RV failure is present.[27]

Predictors of a successful surgical tricuspid valve repair

From the surgical perspectives, a successful TV repair is mild or less TR after surgery. Several studies aimed to identify predictors for recurrent TR after surgery (Table 3). Most studies found severe TR and suture annuloplasty are risk factors of recurrent TR after TV repair. Nevertheless, these studies use survival analyses in the context of repeated measures, which is not the preferred approach.[78] Navia et al.[79] used advanced statistical modelling for repeated echocardiography and showed a higher grade of TR, larger TV annuloplasty ring, presence of pacemaker leads, mitral valve replacement rather than repair, depressed LV function, and advanced LV remodelling to predict TR recurrence. As far as TV morphology is concerned, the tethering distance was found to predict recurrent TR after annuloplasty.[56] As tethering is usually present among inoperable patients who might be the first target population of transcatheter therapy, the question whether a transcatheter annuloplasty alone will be sufficient need to be answered.

Table 3. Risk factors of recurrent tricuspid regurgitation

Study	Risk factors				
	De Vega vs. ring annuloplasty HR (95% CI)	Severe TR at baseline HR (95% CI)	Higher PASP HR (95% CI)	Female gender HR (95% CI)	Atrial fibrillation HR (95% CI)
Ren (2015)[70]	1.47 (1.0–1.9)	NS	1.54 (1.1–2.0)	NS	—
Lin (2014)[71]	7.2 (2.7–15.4)	3.6 (1.7–12.1)	NS	NS	9.4 (2.3–94.0)
Ratschiller (2015)[72]	—	3.0 (1.2–7.8)	—	2.5 (1.0–5.9)	4.3 (1.0–18.3)
Gatti (2016)[73]	2.2 (1.1–4.3)	1.2 (0.6–2.4)	1.3 (0.6–2.9)	—	—
Yoda (2011)[74]	—	8.23[a]	NS	—	NS
Jung (2010)[75]	—	—	—	—	NS
Murashita (2014)[76]	10.7 (3.7–31.0)[b]	2.8 (1.4–5.7)[b]	—	—	—
Ghanta (2007)+	0.64 (0.1–1.2)[c]	4.0 (3.4–4.7)	1.0 (0.9–1.0)	—	—

—, not reported; CI, confidence interval; HR, hazard ratio; NS, not significant upon univariate analyses; PASP, pulmonary arterial systolic pressure; TR, tricuspid regurgitation.

[a]No confidence interval reported.

[b]Only univariable cox regression model.

[c]Kay vs. Ring annuloplasty.

TRICUSPID REGURGITATION THERAPY—INTERVENTIONAL PERSPECTIVE

Following the success of transcatheter aortic valve therapy, there is a large interest in developing transcatheter TV devices. Multiple novel technologies are currently invented for transcatheter TV therapy. Most of these devices are yet in the preclinical or early clinical assessment.[14]

Patient selection

The number of patients treated within these transcatheter TV therapy pilot studies is still limited, and most enrolled patients are inoperable or at 'high surgical risk' with chronic secondary TR (Supplementary material online, Table S2). Considering the heterogenous nature of TR, patient selection by a multidisciplinary heart team is paramount to optimize clinical results and effectiveness of transcatheter TV therapy. We summarized potential target population for future studies investigating whether those patients would benefit from TV interventions (Supplementary material online, Table S3).[80] As to patients with primary TR, there are only few case reports and some patients with primary TR within TriValve registry.[81] There is insufficient evidence regarding feasibility of transcatheter intervention in this heterogeneous population. An individualized approach is mandatory.

Anatomical challenges

The most common anatomical changes in significant TR are annulus dilatation and leaflet tethering. Specific anatomical considerations should be assessed according to different therapeutic targets. We summarize the potential anatomical and pathophysiological constraints of transcatheter TV interventions.

(1) Challenges during catheter navigation

a. The angulation between the annular plane and the superior and inferior venae cava complicates the transvenous access.

b. The loss of anatomical landmarks under pathologic conditions (right atrial and ventricular dilation) complicates catheter navigation and interferes with proper positioning of repair/replacement devices.

c. Pre-existing device leads could interfere with device delivery and deployment.

d. Imaging views and quality, which depends on numerous patient characteristics (i.e. mechanical valves in place, chest deformation, oesophageal anatomy/pathologies) but also on the device used for repair.

(2) Difficultly in proper sizing

a. Tricuspid annulus is significantly larger than other valves and is influenced by volume status which might preclude appropriate sizing and device selection.

b. Flexibility and fragility of the annulus and the surrounding myocardium counteracts fixation and long-term stability of transcatheter TV replacement devices.

(3) Increased risk of thrombosis

a. The low pressure and slow flow in the right heart chambers might provoke device thrombosis.

Approaches for transcatheter tricuspid valve interventions

As shown in Figure 2, most of devices for transcatheter TV therapy are designed to mimic surgical techniques. Currently, themost widely used technique is the edge-to-edge repair using the MitraClip device (Abbott, Santa Clara, CA, USA) in TV position to improve leaflet coaptation.[82] Nevertheless, transcatheter repair cannot replace all the types of surgical repair, and several vendors are currently developing transcatheter heart valves for TV replacement. Despite the growing experience in transcatheter TV interventions, we would like to emphasize that clinical data on most of the devices are not sufficient to conclude on their safety and efficacy.When evaluating these early clinical data, the following issues should be addressed:

(1) Patients enrolled in first-in-man studies differ markedly in terms of TR severity, EROA, vena contracta area, with some studies focusing on severe TR as compared to torrential TR. This has to be considered when efficacy in TR reduction and potential for clinical improvements of different devices/approaches are assessed.

(2) General application and comparison between studies are hindered by the differences in study design.

(3) Clinical and echocardiographic endpoints, device and procedural success, and optimal TR reduction should be clearly defined.

(4) Most of the surgical data on the TV are derived from patients who underwent left-sided heart surgery which is not fully transferable to dedicated transcatheter interventions.

LESSONS LEARNT FROM TRANSCATHETER LEFT-SIDED VALVE THERAPY

Aortic valve

Transcatheter aortic valve replacement has been an established first-line therapy for high-risk and could be an alternative therapy for surgery in patients with aortic stenosis and intermediate and more recently low risk.[83,84] With the progress of transcatheter valve therapy, balloon-expandable transcatheter heart valves, which were designed for the aortic position are now being applied for degenerated bioprostheses in TV position.[85,86] Off-label heterotopic heart valve implantation in the superior/inferior vena cava (preferred is one valve in the inferior vena cava) is currently being tested in patients who are inoperable or at very high surgical risk for TV replacement.[87,88] Furthermore, dedicated orthotopic/heterotopic devices for TR are in development.[89] Navia et al.[90] reported the first-in-man results of the NaviGate valve. Several patients received this bioprothesis with excellent TR reduction.[91] Conduction disturbances requiring pacemaker implantation has been reported in one patient.[14] Tricuspid valve surgery carries

a significant risk of conduction disorders requiring permanent pacemaker implantation.[92] Whether transcatheter TV therapy, particular annuloplasty, and valve replacement, would encounter similar issues is yet unknown.

Mitral valve

Transcatheter therapy for severe functional mitral regurgitation (FMR) associated with HF has increased rapidly recently. Results of two clinical outcome trials, MITRA-FR and COAPT were published.[93,94] Both trials randomly assigned patients with FMR to MitraClip plus guideline-directed optimal medical treatment (GDMT) or GDMT only. MITRA-FR failed to demonstrate the benefit ofMitraClip procedure in terms of a composite endpoint (all-cause death or unplanned hospitalization for HF). Conversely, the COAPT trial showed that the MitraClip procedure significantly reduced HF rehospitalizations and all-cause death during 2-year follow-up. The COAPT trial applied a prespecified approach by a group of HF specialists to evaluate GDMT prior to randomization, and therefore, this trial had a long enrolment period. The conflicting results of the two studies reflect the importance of patient selection before irreversible HF ensues, optimization of medical therapy and the role of a multidisciplinary heart team. The MitraClip device has been applied to the tricuspid position. The feasibility and safety of edge-to-edge TV repair using the MitraClip device has been reported.[45,81]

The Cardioband system (Edwards Lifesciences, Irvine, CA, USA) is a transcatheter direct annuloplasty device that mimics surgical repair. The feasibility study in symptomatic patients with FMR demonstrated that Cardioband implantation was effective in reducing mitral regurgitation and was associated with improvement in HF symptoms.[95] The ACTIVE randomized trial is ongoing to compare Cardioband implantation plus GDMT to GDMT alone in patients with significant FMR (ClinicalTrials.gov identifier: NCT03016975). The tricuspid Cardioband device has CE mark approval and is the first commercially available transcatheter device for the treatment of significant TR. In the TRI-REPAIR study, Cardioband implantation provided favourable clinical and functional outcomes at 6 months.[96]

Nevertheless, how to define an optimal repair is still an unsolved issue. In the recent published mid-term outcomes of TriValve registry including 312 patients with severe TR,[82] procedural success (defined as patient alive at the end of the procedure, with the device successfully implanted and delivery system retrieved, with a residual TR grade ≤2 by the investigators) was achieved in 72.8% of patients and was independently associated with increased mortality. The definition of successful repair remains discrepant across studies investigating transcatheter devices (Supplementary material online, Table S4). In order to adequately compare clinical outcomes after surgical or transcatheter therapy, definitions of clinical endpoints including technical, device, procedural as well as patient success should be refined and standardized in future studies.

CONCLUSIONS

With the development of transcatheter therapy, there has been an increasing focus on the treatment of significant TR. Although early safety and efficacy results of transcatheter TV therapy are encouraging, remaining uncertainties including grade of TR severity (quantitative and qualitative), patient selection, risk stratification, timing of intervention, and definition of successful repair warrant further investigations. Due to the complex nature and interaction between TR and HF, the question as to whether a timely transcatheter TV therapy, a minimal invasive intervention, may change the disease process and improve clinical outcomes remains to be answered in prospective studies. This manuscript uses a novel heart-team approach via a comprehensive and a balanced focus on uncertainties, controversies, step-by-step recommendations, and endpoints definitions in TR therapy. Therefore, it provides a framework for randomized clinical trials and registries in the field of transcatheter TV therapy. Since there is no document on the Tricuspid Valve Academic Research Consortium yet, we believe that this work will pave the road as the foundation for such a needed document.

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SUPPLEMENTARY MATERIAL

Supplemental Table 1. Comparison of guidelines for the management of tricuspid regurgitation

	ACC/AHA guideline[1]	ESC/EACTS guideline[2]
Medical therapy		
Class IIa	Diuretics can be useful for patients with severe TR and signs of right-sided HF (stage D). (Level of Evidence: C)	
Class IIb	Medical therapies to reduce elevated pulmonary artery pressures and/or pulmonary vascular resistance might be considered in patients with severe functional TR (stages C and D). (Level of Evidence: C)	
Surgical therapy		
Class I	Surgery is indicated in patients with: • Severe TR undergoing left- sided valve surgery.	Surgery is indicated in patients with: • **Primary** o Severe primary TR undergoing left-sided valve surgery. o Severe symptomatic isolated primary TR without severe RV dysfunction. • **Secondary** o Severe secondary TR undergoing left-sided valve surgery.
Class IIa	• TV repair can be beneficial for patients with mild, moderate, or greater functional TR at the time of left-sided valve surgery with either tricuspid annular dilation or prior evidence of right HF.	Surgery should be considered in patients with: • **Primary** o Moderate primary TR undergoing left-sided valve surgery. o Asymptomatic or mildly symptomatic patients with severe isolated primary tricuspid TR and progressive RV dilatation or deterioration of RV function. • **Secondary** o Mild or moderate secondary TR with a dilated annulus (≥40 mm or > 21 mm/m2 by 2D echocardiography) undergoing left-sided valve surgery. o After previous left-sided surgery and in absence of recurrent left-sided valve dysfunction, surgery should be considered in patients with severe TR who are symptomatic or have progressive RV dilata- tion/dysfunction, in the absence of severe RV or LV dysfunction and severe pulmonary vascular disease/hypertension.
Class IIb	• Tricuspid valve repair maybe considered for patients with moderate functional TR (stage B) and pulmonary artery hypertension at the time of left-sided valve surgery. (Level of Evidence: C) • Tricuspid valve surgery may be considered for asymptomatic or minimally symptomatic patients with severe primary TR (stage C) and progressive degrees of moderate or greater RV dilation and/or systolic dysfunction. • Reoperation for isolated tricuspid valve repair or replacement may be considered for persistent symptoms due to severe TR (stage D) in patients who have undergone previous left-sided valve surgery and who do not have severe pulmonary hypertension or significant RV systolic dysfunction. (Level of Evidence: C)	Surgery may be considered in patients with: • **Secondary** o Mild or moderate secondary TR when undergoing left-sided valve surgery even in the absence of annular dilatation when previous recent right-HF has been documented.

Supplemental Table 2. Summary of Inclusion Criteria of Studies on Transcatheter Therapies for Tricuspid Regurgitation

SCOUT II (NCT03225612)	**TRILUMINATE** (NCT03227757)	**TRI-REPAIR** (NCT02981953)	**4Tech** (NCT03294200)
Trialign	**MitraClip**	**Cardioband**	**TriCinch**
• **Chronic functional tricuspid regurgitation** with a minimum of moderate tricuspid regurgitation • ≥18 and ≤85 years old • NYHA II, III, or ambulatory IV • Symptomatic despite Guideline Directed medical Therapy, at minimum, patient on diuretic use • patient is at high risk for open heart valve surgery • LVEF ≥35% • Tricuspid valve annular diameter ≤55 mm (or 29 mm/m^2)	• ≥ 18 years and ≤ 90 years • NYHA Functional Class II (conditional), III, or ambulatory IV • No indication for left-sided or pulmonary valve correction. • The Site Heart Team concur the benefit-risk analysis supports intervention of Valvular heart disease and that the subject is at high risk for tricuspid valve surgery. • In the judgement of the TVRS implanting investigator, femoral vein access is determined to be feasible and can accommodate a 25 Fr catheter. • Subject fulfill the echocardiographic Inclusion Criteria • Subjects with moderate or greater (≥2+) Tricuspid Regurgitation determined by the assessment of a qualifying transthoracic echocardiogram (TTE) and transesophageal echocardiogram (TEE) confirmed by the Echocardiography Core Lab (ECL). • Subjects with moderate TR will only be included in the trial if moderate TR is accompanied by a tricuspid annular diameter of ≥ 40mm as measured by the site heart team echocardiographer. • Subjects with tricuspid valve anatomy determined to be suitable for implantation determined by the site heart team.	• **Chronic functional tricuspid regurgitation** with annular diameter ≥ 40 mm with valve Systolic pulmonary pressure ≤ 60mmHg • ≥18 years old • NYHA Class II-IVa • Symptomatic despite Guideline Directed Medical Therapy; at minimum patient on diuretic regimen • LVEF ≥ 30% • Patient is willing and able to comply with all specified study evaluations • The Local Site Heart Team concur that surgery will not be offered as a treatment option • Transfemoral access of the Cardioband is determined to be feasible	• Moderate to severe functional tricuspid regurgitation, defined as: severity 2+ to 4+ (according to semi-quantitative echocardiographic color flow doppler evaluation); and Annular diameter ≥ 40 mm confirmed by echocardiography • ≥ 18 years old • Subject has read and signed the informed consent prior to study related procedures. • Willing and able to comply with all required follow-up evaluations and assessments. • The 'Heart Team' assessment recommends TriCinch Coil Implantation • NYHA Classification ≥ II. • LVEF ≥ 30%. • Heart failure symptoms despite on optimized medical therapy by the local heart team; at minimum subject on diuretic use • Subject has suitable anatomy for investigational device implantation as per imaging requirements

Supplemental Table 3. Potential target population for future studies investigating "whether those groups would benefit from transcatheter tricuspid valve interventions"

Patient phenotype	Rationale
Severe TR undergoing mitral valve edge-to-edge repair	TR could be improved after treatment for MR, but it remains unchanged or deteriorates in some patients[3] and results in a higher mortality rate.[4] Similarly to the conventional surgical approach, the benefits of simultaneous or staged transcatheter treatment for MR and TR should be investigated in selected patients.[5]
Prior left-heart valve surgery	Patients with residual or late significant TR after left-heart valve surgery have higher mortality rates compared to patients with mild or less TR.[6] However, the risk of reoperation for significant TR after left-sided heart valve surgery could be high.[7]
Post-heart transplantation TR	Post-heart transplantation TR could be caused by iatrogenic trauma during endomyocardial biopsy[8] and increases mortality rate.[9]
High-risk patients with severe AS undergoing TAVI	In a large TAVI registry, 24% had significant TR.[10] Residual significant TR is associated with mortality.[11, 12]
Pacemaker/defibrillator lead-induced TV damage	The incidence of worsening TR post device implantation is around 25%.[13] Transcatheter TV therapy plus leadless pacemaker implantation was performed in a case report.[14]
Elderly patients with long-standing AF with "idiopathic" high-grade TR	Clinical features of chronic AF related functional TR include extremely old age, female sex, lower pulmonary artery pressure, prominent enlarged right atrium and excessive dilated tricuspid annulus with impaired contractility.
Prior surgical TV repair	The recurrence of significant TR after surgical TV repair was common.[15] However, the risk of reoperation could be high.[16] Off-label use of transcatheter valve-in-ring was reported in 20 patients.[17] The procedure was effective in reducing TR. However, paravalvular regurgitation was common after procedure and often required transcatheter treatment with occlusion devices in that registry.

Supplemental Table 4. Summary of Definition of Device Success of Studies on Transcatheter Therapies for Tricuspid Regurgitation

Study	Device	Study design	Definition of device/ procedure success
SPACER (NCT02787408)	Forma	Prospective • registry	• Tricuspid regurgitation reduction compared to baseline and tricuspid valve gradient ≤ 5 mmHg
TRILUMINATE (NCT03227757)	MitraClip	Prospective registry	Echocardiographic tricuspid regurgitation reduction at least 1 grade
SCOUT II (NCT03225612)	Trialign	Prospective registry	Successful access, delivery and retrieval of the device delivery system
4Tech (NCT03294200)	TriCinch	Prospective registry	Echocardiographic tricuspid regurgitation reduction at least 1 grade
TRI-REPAIR (NCT02981953)	Cardioband	Prospective registry	Successful access, deployment and positioning of the Cardioband device

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