Transcatheter mitral valve repair: review of current techniques

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Abstract

Mitral regurgitation is common and is associated with excess morbidity and mortality. Despite these poor outcomes, only a minority of affected patients undergo mitral surgery, for several reasons, which underlines the substantial unmet need for treatment for this disorder. Transcatheter mitral valve repair interventions have been developed to treat mitral regurgitation in an undertreated patient population. The aim of this status quo review is to provide an overview of currently available transcatheter mitral valve repair techniques, the different approaches and the clinical outcomes reported so far.

Keywords Mitral valve · Mitral regurgitation · Mitral valve repair

Introduction

Mitral regurgitation (MR) is the most common valvular heart disease, with an incidence of 10% in individuals older than 75 years [1]. Primary MR is a disease of the mitral valve (MV) involving the mitral leaflets, annulus and chords. MR is mostly degenerative or due to tissue alteration and is associated with annular dilatation, prolapse or chord elongation/rupture. Secondary MR is a disease of the left ventricle (LV) with LV dysfunction and dilatation, which leads to annular dilatation and leaflet tethering and thus restricts the systolic closure of MV. Untreated MR leads to a significant increase in morbidity with dyspnoea, atrial fibrillation, LV failure or pulmonary hypertension and death in patients with severe MR [2–4].

Surgical repair of the MV is the gold standard for the treatment of primary MR, as excellent clinical outcomes can be achieved in most patients [5]. In contrast, surgical treatment of secondary MR is controversial. Suboptimal, residual or recurrent MR after surgical repair or replacement of the MV are

frequent clinical problems, and the perioperative morbidity and mortality are not negligible [6–8].

Despite the clinical importance of MR, most patients with severe MR are untreated. Recent studies have revealed that among patients with severe MR and with left ventricular ejection fraction (LVEF) > 50% and < 50%, only 15% and 5%, respectively, are treated by surgery [2]. There are several reasons for this, including the challenging echocardiographic quantification of MR, time of intervention, age, comorbidities and the fact that up 50% of patients older than 75 years decline surgical treatment [2, 8, 9]. In particular, there is an unmet need for a less invasive treatment option for older patients with high operative risk or inoperable clinical status.

Based on the need for less invasive treatment options and the history of success of transcatheter aortic valve replacement, several transcatheter MV repair techniques have been developed over the past decade to treat MR. These techniques can be categorized as coaptation devices, annuloplasty devices, chordal replacement devices and LV remodelling devices (Fig. 1).

The aim of this status quo review is to provide an overview of currently available transcatheter MV repair techniques, the different approaches and the clinical outcomes reported so far. The review includes devices that have been investigated in first-in-human studies or Certificate (CE) Mark or Food and Drug Administration (FDA) pivotal trials, as well as clinical studies. A summary with key characteristics of each transcatheter MV repair device is given in Table 1.

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Fig. 1 Classification of transcatheter mitral valve repair devices according to their anatomic target and mechanism. Status of development is given. LV, left ventricle; MV, mitral valve. “*” means CE Mark and/or FDA approval

Coaptation devices

Coaptation devices can be categorized as direct or enhanced devices.

Direct coaptation devices

Direct coaptation devices are inspired by the Alfieri stitch, a surgical MV repair technique for anchoring the free edge of the mitral leaflet to the corresponding free edge of the facing leaflet (the edge-to-edge technique) [10]. The correction results in a double orifice that improves coaptation and reduces the regurgitant orifice area with reduction of MR. This surgical technique stimulated the development of the first clinically used transcatheter MV repair system, the MitraClip system (Abbott Vascular, Santa Clara, CA, USA) [10, 11]. Currently, two types of devices are routinely used, the MitraClip system and the PASCAL mitral repair system (Edwards Lifesciences, Irvine CA, USA).

MitraClip®

The MitraClip system is the most frequently implanted and best-investigated transcatheter MV repair system worldwide. It consists of a polyester-covered cobalt-chromium V-shaped clip. Using a 24-Fr transvenous, transseptal system, one or more clips are used to approximate the anterior mitral leaflet with the posterior mitral leaflet. Currently, the third generation of the MitraClip system is available in two sizes: the larger XTR and the normal NTR. The MitraClip device is safe, can be used in primary and secondary MR and can be performed with a high rate of procedural success (reduction of MR to $\leq 2+$) [12–16]. The in-hospital mortality rate, reported mostly in high-risk patients, is 2 to 3% [8, 12, 14, 15]. The rate of technical success is about 90% [6–8, 16].

The MitraClip system was evaluated initially in the EVEREST-I (Endovascular Valve Edge-to-Edge Repair Study) and EVEREST-II trials [17, 18]. The final 5-year results of the EVEREST-II trial showed that MitraClip treatment was safe but was less effective in reducing MR than surgical

Table 1 Overview of in-human used and investigated transcatheter mitral valve repair devices

Device type	Device name	Description	Status
Coaptation devices			
Direct	MitraClip (Abbott Vascular)	<ul style="list-style-type: none"> • Transvenous, transseptal approach (24 Fr) • Based on Alfieri edge-to-edge technique • V-shaped clip • 3rd-generation device available in two sizes: XTR and NTR • Indication in patients with severe MR and prohibitive risk for MV surgery 	<ul style="list-style-type: none"> • CE Mark approval gained • FDA approval
	PASCAL Mitral Repair System (Edwards Lifesciences)	<ul style="list-style-type: none"> • Transvenous, transseptal approach (22 Fr) • Based on Alfieri edge-to-edge technique • Two paddles, one spacer, two clasps • Indication in patients with severe MR and prohibitive risk for MV surgery 	<ul style="list-style-type: none"> • CE Mark approval gained • US pivotal trial under way
Enhanced	Mitra-Spacer (Cardiasolutions)	<ul style="list-style-type: none"> • Transapical approach (18 Fr) • Fluid-filled balloon positioned between the mitral leaflets to improve MV coaptation 	<ul style="list-style-type: none"> • First-in-human study under way
Annuloplasty devices			
Direct	Cardioband (Edwards Lifesciences)	<ul style="list-style-type: none"> • Transvenous, transseptal approach (25 Fr) • Adjustable annuloplasty band, anchored by nitinol screws on the atrial side of posterior mitral annulus (from lateral to medial trigone) • Designed to reduce annulus size and MR • Indication in patients with severe, secondary MR and prohibitive risk for MV surgery 	<ul style="list-style-type: none"> • CE Mark approval gained • US pivotal trial under way
	Mitralign (Mitralign, Inc.)	<ul style="list-style-type: none"> • Transfemoral, transventricular approach (14 Fr) • Plication of mitral annulus by two pledgets placed on ventricular side of mitral annulus 	<ul style="list-style-type: none"> • CE Mark trial completed • US pivotal trial planned
	IRIS (Millipede Medical)	<ul style="list-style-type: none"> • Transvenous, transseptal approach • Complete, semirigid annuloplasty ring fixed by multiple anchor elements on atrial side of mitral annulus 	<ul style="list-style-type: none"> • First-in-human study under way
	Amend (Valcare Medical)	<ul style="list-style-type: none"> • Transapical approach • Complete, semirigid, D-shaped annuloplasty ring fixed by 12 anchors on atrial side of mitral annulus 	<ul style="list-style-type: none"> • First-in-human study under way
Indirect	Carillon (Cardiac Dimensions)	<ul style="list-style-type: none"> • Transjugular approach • Curvilinear segment with two self-expanding anchors placed in coronary sinus 	<ul style="list-style-type: none"> • CE Mark approval gained • US pivotal trial under way
	ARTO (MVRX, Inc.)	<ul style="list-style-type: none"> • Transvenous approach • Suture with two anchors, one anchor placed in coronary sinus and one anchor on atrial septum 	<ul style="list-style-type: none"> • First-in-human study under way
Chordal repair			
	NeoChord (NeoChord, Inc.)	<ul style="list-style-type: none"> • Transapical approach • PTFE suture is anchored on free edge of the mitral leaflet and LV apex • Indication in patients with leaflet prolapse 	<ul style="list-style-type: none"> • CE Mark approval gained • FDA approved
	Harpoon (Edwards Lifesciences)	<ul style="list-style-type: none"> • Transapical approach (14 Fr) • Adjustable PTFE chord anchored by knot on mitral leaflet and LV apex • Indication in patients with leaflet prolapse 	<ul style="list-style-type: none"> • CE Mark trial under way
LV remodelling			
	AccuCinch (Ancora Heart)	<ul style="list-style-type: none"> • Transfemoral, transventricular approach • Cable with series of nitinol anchors is placed subvalvularly below the MV • Tension on the cable reduces LV dimensions • Indication in patients with dilated LV and secondary MR 	<ul style="list-style-type: none"> • First-in-human study under way
	VenTouch (Mardil Medical)	<ul style="list-style-type: none"> • Left-sided mini-thoracotomy • Bladder placed around RV and LV • Bladder reduces LV dimensions by inflation of specific localized LV pads 	<ul style="list-style-type: none"> • First-in-human study under way
	BACE (Phoenic Cardiac)	<ul style="list-style-type: none"> • Indication in patients with dilated LV and secondary MR • Slim polyester belt loops and secured at the base of the heart • Inbuilt balloons are connected to subcutaneous ports • Inflation of the system leads to reduction of mitral annular size and secondary MR • Indication in patients with dilated LV and secondary MR 	<ul style="list-style-type: none"> • Early feasibility trial completed

CE, certification mark; FDA, Food and Drug Administration; Fr, French; LV, left ventricle; MR, mitral regurgitation; MV, mitral valve; PTFE, polytetrafluoroethylene; RV, right ventricle; US, United States

repair in surgical candidates, mainly those with primary MR. Advantages were observed in patients aged ≥ 70 years and those with secondary MR [17].

The latest two randomized clinical trials, the COAPT (Clinical Outcome Assessment of the MitraClip Percutaneous Therapy) and MITRA-FR (Percutaneous Repair with the MitraClip Device for Severe Functional/Secondary Mitral Regurgitation) trials, compared the efficacy of MitraClip treatment with that of guideline-directed medical therapy (GDMT) in patients with functional MR. The COAPT trial found lower rates of hospitalization for heart failure and lower all-cause mortality at 24 months in the group treated with MitraClip than in the group treated with GDMT alone [19]. The MITRA-FR trial found no significant differences between patients who underwent percutaneous MV repair with MitraClip in addition to receiving GDMT and those who received GDMT alone [20]. These controversial results stimulated a discussion about selection of patients for MitraClip therapy and the prognostic impact of LV dysfunction in patients with functional MR and heart failure. Both studies differ in the following aspects, which could possibly explain the main differences:

1. Study design and GDMT: COAPT includes only patients with maximally tolerated GDMT at baseline with few major changes during follow-up vs. HF medication in baseline with allowed variable adjustments during follow-up in the MITRA-FR group;
2. Effective regurgitation orifice area (EROA) and left ventricular end-diastolic volume (LVEDV): EROA was $41 \pm 15 \text{ mm}^2$ in COAPT vs. $31 \pm 10 \text{ mm}^2$ in MITRA-FR as well as LVEDV was $135 \pm 35 \text{ mL/m}^2$ in COAPT vs. $101 \pm 34 \text{ mL/m}^2$ in MITRA-FR;
3. Procedural success: MR $\geq 3+$ in COAPT vs. MITRA-FR at discharge 5% vs. 9% and at 12 months 5% vs. 17%, respectively.

In summary, EROA was higher and LVEDV was lower in COAPT in comparison with MITRA-FR. Patients in COAPT showed a higher procedural success as MITRA-FR. Besides these main differences between the baseline data and treatment of MR in both cohorts, the new conceptual framework of proportionate and disproportionate functional MR may explain further the differences between the results of the two randomized clinical trials, but further investigations are needed [21].

PASCAL mitral repair system

The PASCAL (PAddles Spacer Clasps ALfieri) implant consists of a 10-mm central spacer that is attached to the MV leaflets by two paddles and clasps. The paddles and clasps are wide and should allow load across the surface areas of

the inserted leaflets; the convex curvature of the tips of the paddles aims to reduce tension on the MV leaflets [22, 23]. The clasps can be operated simultaneously or independently, which allows an optional separate grasping of each mitral leaflet. One or more devices can be implanted using a 22-Fr transvenous, transseptal system. A multicentre, prospective, observational, first-in-human study demonstrated the feasibility of the PASCAL system with a high rate of technical success and reduction of MR. The 30-day mortality was 13% in this high-risk cohort [23].

Third and fourth edge-to-edge repair devices are undergoing preclinical testing: the Mitraflex system (TransCardiac Therapeutics, Atlanta, GA, USA) and the Cardica Mitral Repair system (AesDex, LLC, Palo Alto, CA, USA) (Fig. 1).

Enhanced coaptation devices

Enhanced coaptation devices reduce MR by occupying space in the MV orifice and increasing native leaflet coaptation.

Mitra-Spacer

One device is the Mitra-Spacer (Cardiosolutions, Inc., West Bridgewater, MA, USA) [24]. The transapical implanted (18 Fr) Mitra-Spacer is a fluid-filled balloon that is positioned between the two mitral leaflets. The balloon is made of Elast-Eon (AorTech, Weybridge, Surrey, UK), a non-thrombotic polymer, and is apically anchored by a HeartPad (B. Braun, Melsungen, Germany). The balloon has a subcutaneous port for later adjustment by fluid retrieval or filling. During the first-in-human implantation, the Mitra-Spacer was successfully technically implanted, and MR was reduced to moderate. Despite anticoagulation, thrombi developed around the device, and the valve was replaced at 8 months [24].

Based on the surgical experience with MV repair, the absence of annuloplasty limits transcatheter coaptation approaches in terms of effectiveness and durability. The combination of transcatheter edge-to-edge repair and annuloplasty device could improve the clinical outcome and overcome the limits in the future.

Annuloplasty devices

Transcatheter annuloplasty devices imitate surgical annuloplasty by ring or band. The annuloplasty device should reduce the size of the dilated mitral annulus to normal or prevent annular enlargement. Transcatheter annuloplasty devices can be categorized as direct and indirect devices. The most extensive clinical experience is with the Cardioband (Edwards Lifesciences, Irvine, CA,

USA) and Carillon (Cardiac Dimensions, Kirkland, WA, USA) systems.

Direct annuloplasty devices

Direct percutaneous annuloplasty devices use anchors or sutures to implant the device on the atrial or ventricular side of the mitral annulus. The devices reduce the size of the mitral annulus, improving mitral coaptation and reducing MR.

Cardioband mitral system

The Cardioband mitral system is a direct annuloplasty system for the treatment of secondary MR. It is delivered via a transvenous, transseptal approach. The Cardioband is an open adjustable Dacron band, anchored by 6-mm-long multiple nitinol screws from the lateral to the medial trigone. After implantation, the Cardioband is cinched to reduce annular dimensions and MR.

In a feasibility trial in 31 patients with functional MR, transcatheter mitral annuloplasty with Cardioband was effective in reducing MR and was associated with improvement in heart failure symptoms and demonstrated a favourable safety profile. The anteroposterior diameter was reduced by >30% from 3.7 ± 0.5 cm at baseline to 2.5 ± 0.4 cm after 1 month and 2.4 ± 0.4 cm after 6 months. The residual MR grade was ≤ 2 in 86.3% of patients at 6-month follow-up [25, 26]. In a single-arm, prospective multicentre trial in 60 symptomatic patients, the rates of functional, technical device and procedural success, based on Mitral Valve Academic Research Consortium (MVARC) criteria, were 97%, 72% and 68%, respectively. At 1 year, the rates of overall survival, survival free of readmission for heart failure and survival free of reintervention were 87%, 66% and 78%, respectively. There were one stroke, two coronary artery complications, one tamponade and 10 anchor disengagements (all but one in the first half of the population), resulting in device inefficacy in five patients and leading to device modification halfway through the study to mitigate this issue [27].

Mitralign

The Mitralign system (Mitralign, Tewksbury, MA, USA) is a percutaneous 14-Fr transfemoral, transventricular annuloplasty system. A pair of pledgets are plicated and locked on the ventricular side of the mitral annulus to reduce annular dilatation and MR. The feasibility and safety of the system were demonstrated in a first-in-human study. Echocardiographic analysis at 6 months showed MR reduction in 50% of treated patients [28].

IRIS transcatheter annuloplasty ring

The IRIS annuloplasty system (Millipede Medical, Santa Rosa, CA, USA) is a semirigid complete adjustable ring with a nitinol frame, which is placed on the atrial side of the mitral annulus by multiple anchor elements. The system is placed via a transvenous, transseptal approach. The first-in-human implantation was announced in May 2017 [29].

Amend™

The Amend system (Valcare Medical, Herzliya Pituah, Israel) is a complete, semirigid, D-shaped mitral annuloplasty ring. The annuloplasty ring is fixed by 12 anchors on the atrial side of the mitral annulus via a transapical approach. First-in-human implantation was recently reported [30].

Several other transcatheter direct annuloplasty devices are under preclinical testing: Mitral Restriction Ring (Cardiac Implant Solutions, Jacksonville, FL, USA), Kardium MR (Kardium, Burnaby, BC, Canada) and QuantumCor (QuantumCor, Lake Forest, CA, USA).

Indirect annuloplasty devices

Indirect annuloplasty devices are placed by sutures or anchors on the left atrium or coronary sinus in close proximity to the mitral annulus.

Carillon® mitral contour system

The Carillon mitral contour system (Cardiac Dimensions, Kirkland, WA, USA) consists of two self-expanding nitinol anchors connected by a nitinol curvilinear segment. The system is delivered transjugularly in the coronary sinus and indirectly reduces the annular dimensions. A feasibility trial in patients with secondary MR showed safety with significant reduction of MR from the EROA from 0.23 ± 0.07 cm² to 0.12 ± 0.08 cm² at 1-year follow-up [31]. Comparison of treated patients with a pseudocontrol consisting of patients without implants showed improvement of functional and performance status in the treated group [32]. Randomized clinical trials comparing the Carillon system with sham procedure or GDMT are under way. Despite the clinical improvement in patients treated by Carillon, the system has several limitations: the efficiency of the system depends on the anatomy of the coronary sinus and mitral annulus. Further, there is a risk of coronary obstruction that may preclude patient eligibility [8].

ARTO™ system

The ARTO system (MVRX, San Mateo, CA, USA) consists of a suture connected to two anchors. During the transvenous procedure, one anchor is placed in the interatrial septum and the second anchor is placed in the coronary sinus. Tension on the suture reduces the annular anteroposterior diameter, resulting in improvement of coaptation and reduction of MR [33]. The first-in-human Mitral Valve Repair Clinical (MAVERIC) trial in 11 patients with symptomatic heart failure and secondary MR demonstrated safety and meaningful efficacy [34].

Chordal replacement devices

Chordal replacement devices should restore coaptation and MV function by artificial chordal replacement and are mainly used in patients with primary MR. The largest experience is with the NeoChord device (NeoChord, St. Louis Park, MN, USA).

NeoChord DS1000

The NeoChord DS1000 is an echo-guided, transapical, catheter-based device for implantation of adjustable polytetrafluoroethylene (PTFE) sutures for treatment of primary MR. The PTFE suture is fixed on the free edge of the mitral leaflet and is adjusted in real time under echocardiographic control. After adjustment of the length of the PTFE suture, the suture is fixed at the apex of the LV by pledgets. Multiple implantation of PTFE sutures in addition to leaflet pathology is possible.

The safety and feasibility of the NeoChord DS1000 were demonstrated in the Transapical Artificial Chordae Tendinae (TACT) feasibility trial [35]. The efficacy and durability depended on the complexity of MV leaflet morphology. Patients with a wide P2 and/or P3 prolapse were identified as most suitable (94%) for the composite end point (mortality, MR recurrence, mitral surgery, rehospitalisation and stroke at 1 year). Bileaflet or commissural pathologies decreased the rates of success and durability to 82% and 63% (for the composite end point at 1 year), respectively [36, 37]. Successful implantation of the NeoChord leads to improvement of clinical status with good mid-term durability [38–40]. Several clinical trials are under way to analyse the efficacy of the NeoChord in comparison with surgical MV repair.

Harpoon TSD-5

The Harpoon TSD-5 device (Edwards Lifesciences, Irvine, CA, USA) is a 14-Fr, echo-guided, transapical chordal replacement device, which allows the implantation of multiple

and adjustable PTFE chordae. The mitral leaflet is anchored by a preformed knot (instead of free-edge leaflet fixation with NeoChord), which should improve long-term durability [41]. Safety and feasibility were demonstrated in the initial feasibility trial in 30 patients with severe degenerative MR. At 1 month, MR was mild or less in 89% of patients and moderate in 11% of patients. At 6 months, MR was mild or less in 85% of patients, moderate in 8% of patients and severe in 8% of patients [42].

ChordArt™

The ChordArt device (Coremedic GmbH, Tuebingen, Germany) uses an antegrade transvenous, transseptal approach for implantation of premeasured artificial chordae. The distal parts of the chordae are fixed by an anchor directly to the papillary muscle. The device is in preclinical validation, and a first-in-human trial is planned for 2019. The ChordArt system overcomes the limitations of the transapical devices (e.g. bleeding) [8].

The technical success, efficacy and durability of transcatheter chordal replacement devices clearly depend on patient selection, which remains the critical point of this technique. Based on the experience with surgical MV repair in patients with primary MR, it is questionable whether the durability of this technique is comparable with that of surgical MV repair in the absence of ring or band annuloplasty. One possible solution for the future could be a combination of transcatheter chordal replacement and annuloplasty devices in patients with MV prolapse.

Several other devices are under preclinical testing, including the MISTRAL chordal repair system (Mitralix, Jerusalem, Israel) and the V-Chordal TF (Valtech Cardio, Or Yehuda, Israel).

LV remodelling devices

LV remodelling devices address the reduction of LV dimension in the presence of secondary MR caused by ischemic or non-ischaemic cardiomyopathy. These devices should reduce the distance from the LV wall and papillary muscle to the mitral annulus and leaflets, which should improve MV competence.

AccuCinch®

The AccuCinch system (Ancora Heart, Santa Clara, CA, USA) consists of a cable with a series of nitinol anchors that are implanted subvalvularly on the ventricular side of the MV, using a transfemoral, retroaortic approach. The tension on the cable results in a ventriculoplasty, leading to MR reduction.

The AccuCinch system is under investigation in early first-in-human studies [43].

VenTouch™

The VenTouch system (Mardil Medical, Minneapolis, MN, USA) consists of a bladder that is placed via a left-sided mini-thoracotomy around the left and right ventricles. The inflation of specific LV pads should reduce LV and mitral annular dimensions, resulting in improvement of mitral leaflet coaptation [44]. A first-in-human study has been initiated.

BACE

The BACE (Basal Annuloplasty of the Cardia Externally) device (Phoenix Cardiac Devices, Cary, NC, USA) is implanted by means of slim polyester belt loops, and secured at the base of the heart. This device can be adjusted remotely under echocardiographic guidance, by inflating the inbuilt balloons that are connected to subcutaneous ports [45, 46]. The inflation of balloons by saline leads to a reduction of dilated mitral annulus and LV dilatation with subsequent reduction of MR. An early feasibility trial in 11 patients demonstrates the safety of a beating-heart reduction of secondary MR and sustained benefit in preventing HF progression [46].

Clinical implications

The field of transcatheter MV therapy is quickly evolving, and the clinical need for safe and effective devices is still largely unmet [47]. Currently, 13 different transcatheter MV devices are used in humans (CE Mark and/or FDA approved, CE Mark trial and/or FDA pivotal trial, first-in-human studies), of which five devices have CE Mark and/or FDA approval for routine clinical use in patients who are at prohibitive risk for surgery (Fig. 2, Table 1). These devices are the MitraClip, Cardioband, PASCAL, NeoChord and Carillon. Of these, the clinical evidence and experience are most extensive for the MitraClip and the NeoChord systems. All approved devices should be used in patients with high operative risk or inoperable status (Fig. 3).

Decision-making and device selection should be performed by a multidisciplinary heart valve team according to current guidelines and recommendations [48, 49]. Shared decision-making for the selection of transcatheter MV therapy should be performed by a multidisciplinary heart valve team with interventionalists, mitral surgeons, imaging experts, anaesthesiologists, valve experts and a nurse care team. Aetiology and severity, symptoms, LV function, associated conditions (e.g. atrial fibrillation,

coronary artery disease), comorbidities, risk assessment and functional status should be evaluated before the heart valve team selects a patient for transcatheter MV repair therapy or enrolment in a clinical trial [50]. For device selection, the feasibility of transcatheter MV repair devices in patient-specific pathoanatomical characteristics of the MV complex should be proven. Because of the great anatomic variability of MR, interventionalists will likely need to develop interventional expertise with more than one transcatheter MV repair device and with advanced imaging techniques such as two-dimensional/three-dimensional echocardiography, computed tomography (CT)-based planning, fluoroscopy and imaging fusion techniques [47].

Future perspectives on transcatheter mitral valve repair

Decision-making between the different approaches depends mainly on MV pathology, the anatomic inclusion and exclusion criteria for the different devices, the experience of the interventionalist and the availability of the different devices, including their cost. Most of these devices are in preclinical or early clinical investigation (first-in-human studies, CE Mark or FDA pivotal trials) and are only used in patients with high operative risk or in compassionate cases. Current results showing a high safety profile, but eligibility, effectiveness and durability, require further investigation [8].

Effectiveness and durability are the main concerns of these novel techniques, mainly due to the fact that all devices address only one anatomic part of the MV complex in patients with MR. Based on the experience with surgical MV repair, excellent functional results and durability after MV repair can only be achieved with a deep understanding of MV pathology, surgical experience, a wide spectrum of different repair techniques (e.g. different annuloplasty ring types, sliding plasty and resection techniques, artificial chordal replacement, chordal cutting and papillary muscle approximation) and consideration of the risk factors for repair failure. The combination of different transcatheter MV repair techniques and the investigation of risk factors for transcatheter MV repair failure can be a possible approach to improve effectiveness and durability [51].

It can be assumed that transcatheter MV repair techniques will be developing from a palliative approach towards improving the prognosis in early indication [8]. Therefore, work in a multidisciplinary heart valve team with joint decision-making, more clinical evidence, technical improvements of the devices, optimal patient screening and procedural guidance, as well as more procedural experience, are mandatory for revolutionizing MV treatment.

Fig. 2 In-human used transcatheter mitral valve repair devices. **a** MitraClip. **b** PASCAL. **c** Mitra-Spacer. **d** Cardioband. **e** Amed. **f** IRIS. **g** Carillon. **h** ARTO. **i** NeoChord. **j** Harpoon. **k** AccuCinch. **l** VenTouch

Besides the fast developments in transcatheter MV repair techniques, transcatheter MV replacement techniques are also introduced in the treatment of MR with multiple platforms and devices. The safe anchoring in the native MV, the commonly transapical access (> 32 Fr) and the risk of left ventricular out-flow track (LVOT) obstruction are technically challenging in this high-risk cohort with enlarged and thin myocardium. These concerns are associated with an elevated early mortality (6–14%) during the first feasibility trials. The most implanted transcatheter MV valve worldwide, the Tendyne™ valve (Abbott Vascular, Santa Clara, CA, USA), has shown an

acceptable safety profile (30-day mortality, 6%; 1-year survival, 74%) with highly effective in relieving MR (none/trivial MR at 12 months, 98.4%) and improving symptoms (NYHA functional class ≤ II at 12 months, 62.8%) [52]. Residual and recurrent MR are clinically common after treatment with transcatheter MV repair techniques. In patients with secondary MR, transcatheter MV replacement may be more effective than repair [53]. The choice of repair versus replacement is complex and needs to be individualized [44]. Further investigations are needed to clarify potential clinical pathway for treatment of severe, symptomatic MR with transcatheter MV techniques.

Fig. 3 Management pathway for patients with severe mitral regurgitation and indication for intervention. Only transcatheter mitral valve (MV) devices with CE Mark and/or FDA approval are given. MR, mitral

regurgitation. “*” means combination of two different CE Mark and/or FDA approved transcatheter mitral valve repair devices

Conclusion

Mitral regurgitation is common and is associated with excess mortality and frequent heart failure postdiagnosis. Despite these poor outcomes, only a minority of affected patients undergo mitral (or any other type of cardiac) surgery, for several reasons, which underlines the substantial unmet need for treatment for this disorder [2].

Transcatheter MV repair techniques are clinically relevant treatment options for MR in an undertreated patient population. Several clinical investigations in this highly dynamic field of cardiovascular medicine have demonstrated the safety

and feasibility of these techniques. Effectiveness and durability are the main concerns of transcatheter MV repair approaches and must be improved in the future. Multidisciplinary decision-making and careful patient selection are mandatory for the treatment of MR with transcatheter MV repair devices.

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