



# The management of secondary mitral regurgitation in patients with heart failure: a joint position statement from the Heart Failure Association (HFA), European Association of Cardiovascular Imaging (EACVI), European Heart Rhythm Association (EHRA), and European Association of Percutaneous Cardiovascular Interventions (EAPCI) of the ESC

Andrew J.S. Coats <sup>1\*</sup>, Stefan D. Anker<sup>2,3,4,5</sup>, Andreas Baumbach <sup>6\*</sup>,  
Ottavio Alfieri <sup>7</sup>, Ralph Stephan von Bardeleben <sup>8</sup>, Johann Bauersachs <sup>9</sup>,  
Jeroen J. Bax<sup>10</sup>, Serge Boveda <sup>11</sup>, Jelena Čelutkienė<sup>12,13</sup>, John G. Cleland <sup>14</sup>,  
Nikolaos Dargatzis <sup>15</sup>, Thomas Deneke<sup>16</sup>, Dimitrios Farmakis<sup>17</sup>,  
Gerasimos Filippatos <sup>18</sup>, Jörg Hausleiter <sup>19</sup>, Gerhard Hindricks<sup>15</sup>,  
Ewa A. Jankowska<sup>20</sup>, Mitja Lainscak<sup>21,22</sup>, Christoph Leclercq <sup>23</sup>, Lars H. Lund<sup>24</sup>,  
Theresa McDonagh <sup>25</sup>, Mandeep R. Mehra <sup>26</sup>, Marco Metra <sup>27</sup>,  
Nathan Newton<sup>28</sup>, Christian Mueller <sup>29</sup>, Wilfried Mullens<sup>30,31</sup>,  
Claudio Muneretto<sup>32</sup>, Jean-Francois Obadia <sup>33</sup>, Piotr Ponikowski<sup>20</sup>,  
Fabien Praz <sup>34</sup>, Volker Rudolph <sup>35</sup>, Frank Ruschitzka <sup>36</sup>, Alec Vahanian <sup>37</sup>,  
Stephan Windecker <sup>34</sup>, Jose Luis Zamorano<sup>38,39,40</sup>, Thor Edvardsen <sup>41,42†</sup>,  
Hein Heidbuchel<sup>43†</sup>, Petar M. Seferovic<sup>44†</sup>, and Bernard Prendergast <sup>45†</sup>

<sup>1</sup>Warwick Medical School, University of Warwick, Coventry, UK; <sup>2</sup>Department of Cardiology (CVK), Germany; <sup>3</sup>Berlin Institute of Health Center for Regenerative Therapies (BCRT), Germany; <sup>4</sup>German Centre for Cardiovascular Research (DZHK) partner site Berlin, Germany; <sup>5</sup>Charité Universitätsmedizin Berlin, Germany; <sup>6</sup>Centre for Cardiovascular Medicine and Devices, William Harvey Research Institute, Queen Mary University of London, and Yale University School of Medicine, New Haven, USA; <sup>7</sup>Department of Cardiac Surgery, San Raffaele Scientific Institute, Milan, Italy; <sup>8</sup>Heart Valve Center Mainz, Center of Cardiology, Cardiology I, University Medical Center, Mainz, Germany; <sup>9</sup>Department of Cardiology and Angiology, Hannover Medical School, Hannover, Germany; <sup>10</sup>Department of Cardiology, Leiden University Medical Centre, Leiden, The Netherlands; <sup>11</sup>Department of Cardiology, Clinique Pasteur, 31076 Toulouse, France; <sup>12</sup>Clinic of Cardiac and Vascular Diseases, Institute of Clinical Medicine, Faculty of Medicine, Vilnius University, Vilnius, Lithuania; <sup>13</sup>State Research Institute Centre For Innovative Medicine, Vilnius, Lithuania; <sup>14</sup>Robertson Centre for Biostatistics & Clinical Trials, University of Glasgow, Glasgow, UK; <sup>15</sup>Department of Electrophysiology, Heart Center Leipzig at University of Leipzig, Leipzig, Germany; <sup>16</sup>Heart Center Bad Neustadt, Clinic for Interventional Electrophysiology, Germany; <sup>17</sup>University of Cyprus Medical School, Nicosia, Cyprus; <sup>18</sup>Heart Failure Unit, Department of Cardiology, Athens University

\* Corresponding authors. Tel: +44-7551528636, Email: [a.coats@warwick.ac.uk](mailto:a.coats@warwick.ac.uk) (A.J.S.C.); Tel: +44-203-765-8740, Email: [a.baumbach@qmul.ac.uk](mailto:a.baumbach@qmul.ac.uk) (A.B.)

†These authors contributed equally to this work.

© The Author(s) 2021. Published by Oxford University Press on behalf of the European Society of Cardiology.

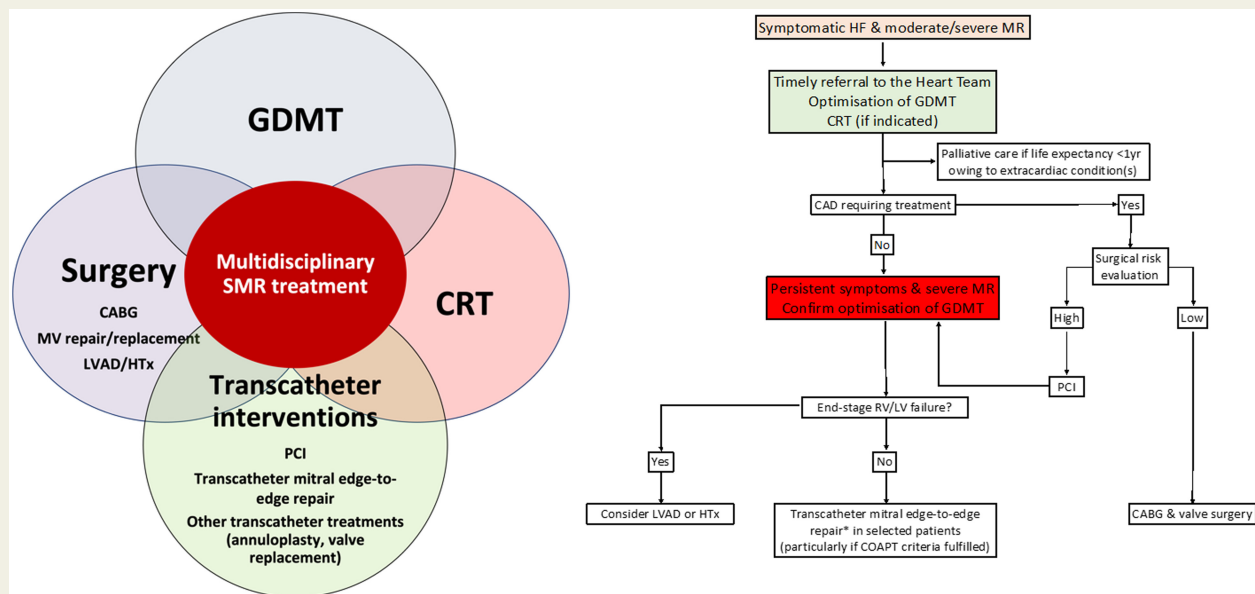
This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact [journals.permissions@oup.com](mailto:journals.permissions@oup.com)

Hospital Attikon, National and Kapodistrian University of Athens, Athens, Greece; <sup>19</sup>Department of Medicine I, University Hospital Munich, Ludwig-Maximilians University Munich, Germany; <sup>20</sup>Department of Heart Diseases, Wrocław Medical University and Centre for Heart Diseases, University Hospital, Wrocław, Poland; <sup>21</sup>Division of Cardiology, General Hospital Murska Sobota, Murska Sobota, Slovenia; <sup>22</sup>Faculty of Medicine, University of Ljubljana, Ljubljana, Slovenia; <sup>23</sup>Université de Rennes I, CICIT 804, Rennes, CHU Pontchaillou, France, Rennes; <sup>24</sup>Department of Medicine, Karolinska Institutet and Heart and Vascular Theme, Karolinska University Hospital, Stockholm, Sweden; <sup>25</sup>King's College Hospital, London, UK; <sup>26</sup>Brigham Women's Hospital Heart and Vascular Center and the Center of Advanced Heart Disease, Harvard Medical School, Boston, USA; <sup>27</sup>Cardiology, Department of Medical and Surgical Specialties, Radiological Sciences, and Public Health, University of Brescia, Italy; <sup>28</sup>Hôpital Cardio-Vasculaire Louis Pradel, Centre d'Investigation Clinique, Filère Insuffisance Cardiaque, e, France, Lyon; <sup>29</sup>Department of Cardiology and Cardiovascular Research Institute Basel (CRIB), University Hospital Basel, University of Basel, Switzerland; <sup>30</sup>Department of Cardiology, Ziekenhuis Oost-Limburg, Genk, Belgium; <sup>31</sup>Faculty of Medicine and Life Sciences, Biomedical Research Institute, Hasselt University, Diepenbeek, Belgium; <sup>32</sup>School of Cardiac Surgery, University of Brescia, Italy; <sup>33</sup>Department of Cardiac Surgery, "Louis Pradel" Cardiologic Hospital, Lyon, France; <sup>34</sup>Department of Cardiology, Inselspital, University of Bern, Bern, Switzerland; <sup>35</sup>Clinic for General and Interventional Cardiology/Angiology, Herz- und Diabeteszentrum NRW, Ruhr-Universität Bochum, Bad Oeynhausen, Germany; <sup>36</sup>Cardiology Clinic, University Heart Center, University Hospital Zürich, Switzerland; <sup>37</sup>University of Paris, Paris, France; <sup>38</sup>Cardiology Department, University Hospital Ramon y Cajal, Madrid, Spain; <sup>39</sup>University Alcala, Madrid, Spain; <sup>40</sup>CIBERCV, Instituto de Salud Carlos III, Madrid, Spain; <sup>41</sup>Department of Cardiology, Centre of Cardiological Innovation, Oslo University Hospital, Rikshospitalet, Oslo, Norway; <sup>42</sup>Institute for Clinical Medicine, University of Oslo, Oslo, Norway; <sup>43</sup>Antwerp University and Antwerp University Hospital, Antwerp, Belgium; <sup>44</sup>Faculty of Medicine, University of Belgrade, Belgrade, Serbia; and <sup>45</sup>Department of Cardiology, St Thomas' Hospital, Westminster Bridge Road, London, UK

Received 10 December 2020; revised 1 January 2021; editorial decision 1 February 2021; accepted 21 February 2021; online publish-ahead-of-print 18 March 2021

Secondary (or functional) mitral regurgitation (SMR) occurs frequently in chronic heart failure (HF) with reduced left ventricular (LV) ejection fraction, resulting from LV remodelling that prevents coaptation of the valve leaflets. Secondary mitral regurgitation contributes to progression of the symptoms and signs of HF and confers worse prognosis. The management of HF patients with SMR is complex and requires timely referral to a multidisciplinary Heart Team. Optimization of pharmacological and device therapy according to guideline recommendations is crucial. Further management requires careful clinical and imaging assessment, addressing the anatomical and functional features of the mitral valve and left ventricle, overall HF status, and relevant comorbidities. Evidence concerning surgical correction of SMR is sparse and it is doubtful whether this approach improves prognosis. Transcatheter repair has emerged as a promising alternative, but the conflicting results of current randomized trials require careful interpretation. This collaborative position statement, developed by four key associations of the European Society of Cardiology—the Heart Failure Association (HFA), European Association of Percutaneous Cardiovascular Interventions (EAPCI), European Association of Cardiovascular Imaging (EACVI), and European Heart Rhythm Association (EHRA)—presents an updated practical approach to the evaluation and management of patients with HF and SMR based upon a Heart Team approach.

## Graphical Abstract



## Keywords

Heart failure • Secondary mitral regurgitation • Functional mitral regurgitation • Transcatheter mitral valve repair

## Introduction and scope

Moderate or severe secondary (also known as functional) mitral regurgitation (SMR) accompanies heart failure (HF) in about one-third of patients<sup>1</sup> and contributes to clinical deterioration, progression of the syndrome, and adverse outcomes.<sup>2–5</sup> Secondary mitral regurgitation results from left ventricular (LV) remodelling as a consequence of ischaemic or non-ischaemic myocardial disease that leads to reduced coaptation of normal mitral valve leaflets via several mechanisms.<sup>6</sup> Since SMR is principally a disease of the left ventricle and not of the valve itself, current treatment strategies target the underlying LV disorder. However, SMR exaggerates LV remodelling by increasing volume load and mechanical correction has been proposed alongside guideline-directed medical therapy (GDMT) to improve symptoms and prognosis.

The interventional management of patients with HF and SMR is challenging. In contrast to primary (including degenerative) mitral regurgitation (MR), the outcomes of surgical mitral valve repair, either alone or combined with coronary artery bypass grafting (CABG), are of questionable benefit.<sup>7–9</sup> Transcatheter techniques for the correction of SMR have broadened the spectrum of patients who may benefit from mitral valve intervention, although current European Society of Cardiology (ESC) guidelines for the management of both HF and valvular heart disease (VHD) indicate the need for further clinical research in this area.<sup>10,11</sup> The recently published COAPT<sup>12</sup> and MitraClip Device for Severe Functional/Secondary Mitral Regurgitation (MITRA-FR)<sup>13</sup> randomized controlled trials have addressed this deficit but their conflicting results have generated considerable discussion and require careful interpretation.

This position statement, developed in collaboration by the ESC Heart Failure Association (HFA), European Association of Cardiovascular Imaging (EACVI), European Heart Rhythm Association (EHRA), and European Association of Percutaneous Cardiovascular Interventions (EAPCI), proposes an updated practical approach to the management of patients with HF and SMR based on a multidisciplinary Heart Team approach. We outline the current evidence (and its limitations), discuss open issues that need to be addressed by future research, and stress the importance of appropriate referral and selection of patients for transcatheter mitral valve intervention alongside guideline-recommended medical and device therapies.

## Pathophysiology

The pathophysiology of SMR is complex (*Figure 1*), reflecting imbalance between valve closing and leaflet tethering forces, and the dynamic impact of factors affecting LV preload and afterload in patients with LV remodelling due to ischaemic or non-ischaemic myocardial disease.<sup>6,15–18</sup>

Progressive SMR is a marker of poor prognosis in patients with chronic HF<sup>4,19</sup> and the transition from LV disease 'marker' to HF 'contributor' is critical in determining the need for valve intervention. The concept of 'proportionate' and 'disproportionate' MR,<sup>20</sup> based upon a modelled relationship between LV end-diastolic volume and effective regurgitant orifice area (EROA), and its disruption in

patients with ventricular dyssynchrony or papillary muscle dysfunction, has been proposed to guide the mode of treatment and predict the impact of transcatheter intervention. Although attractive from a pathophysiological point of view, this theoretical model overlooks the need to assess the severity of MR using an integrated multi-parametric approach (and, in particular, fails to consider the frequently elliptical regurgitant orifice in SMR) and has not been validated to date.

Secondary mitral regurgitation may also arise as a consequence of left atrial enlargement and mitral annular dilatation/flattening in patients with longstanding atrial fibrillation (AF), where left ventricular ejection fraction (LVEF) is often normal and LV dilatation less pronounced. So-called 'atrial'<sup>21,22</sup> MR may also contribute to SMR in patients with HF and AF. This pathophysiological distinction is important since treatment options differ.

## Epidemiology and prognosis

Moderate or severe MR is present in about one-third of HF patients.<sup>1</sup> Early studies indicated that MR is an independent predictor of clinical HF and major cardiac events following acute myocardial infarction or in patients with LV dysfunction.<sup>23,24</sup> More contemporary data confirm that SMR is associated with adverse clinical outcomes, independent of clinical, haemodynamic, echocardiographic, and neuro-hormonal confounders. In a cohort of 576 HF patients with reduced LV ejection fraction (HFrEF) on optimal medical therapy, severe SMR was associated with mortality in intermediate-severity HF New York Heart Association (NYHA) class II/III, LVEF 30–40% and N-terminal pro brain natriuretic peptide (NT-proBNP) 871–2360 pg/mL], but not in those with more advanced disease.<sup>4</sup>

## Clinical and imaging assessment

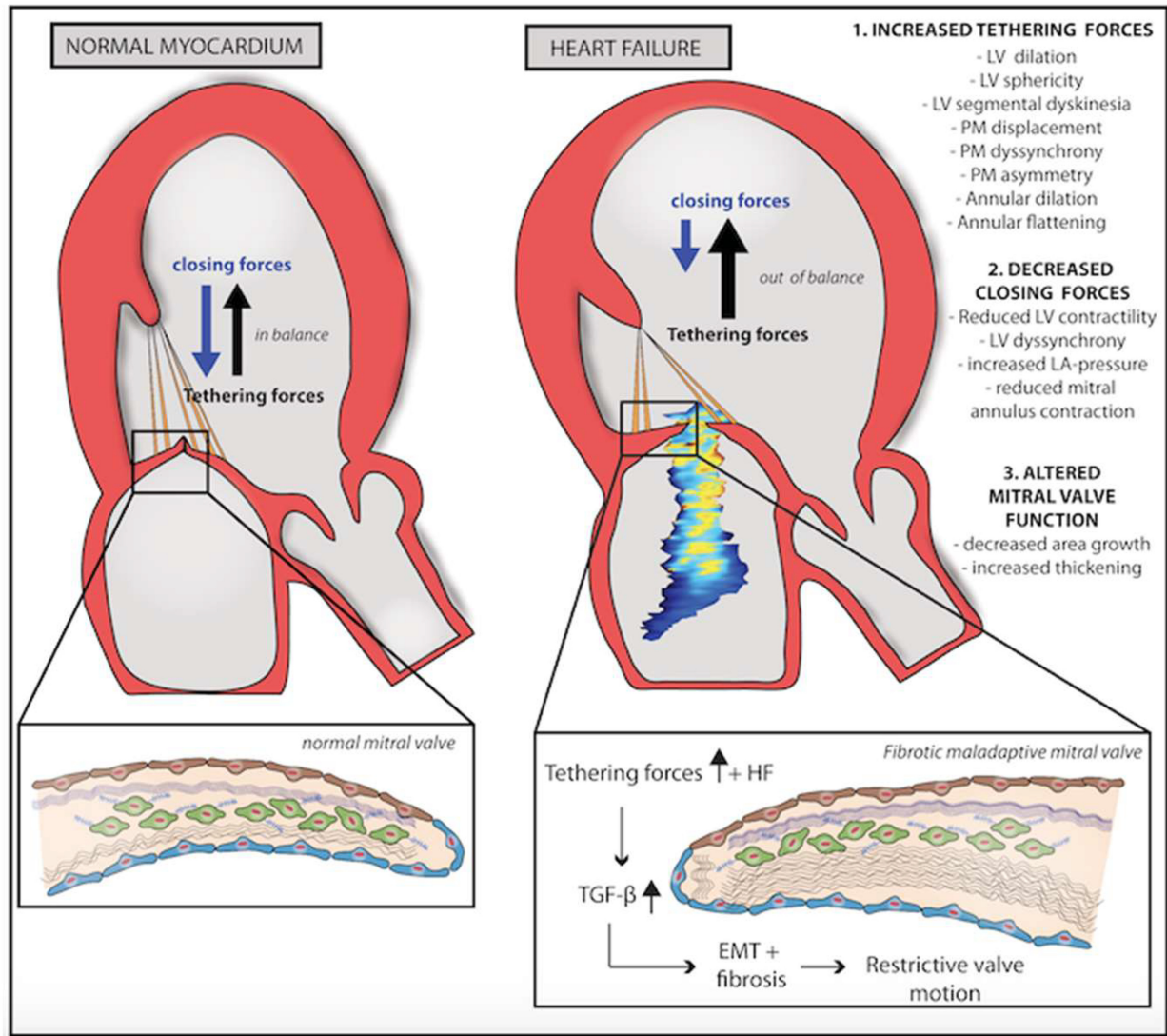
Initial evaluation of patients with HF and SMR should include:

- History and physical examination (to define functional, haemodynamic, and volume status, and HF severity).
- Electrocardiogram (to demonstrate baseline rhythm and QRS duration).
- Laboratory measurements (haemoglobin, renal function, and natriuretic peptides),
- Evaluation of LV function (including the presence of myocardial scar/viability),
- Invasive or non-invasive coronary angiography.

## Imaging modalities

Transthoracic echocardiography facilitates integrated structural and functional assessment of the mitral valve, LV, and left atrium (together with associated valve disease, right ventricular function, and estimated pulmonary pressure) and is the key initial screening tool for standardized measurement of LV function and MR severity.<sup>11,25</sup>

Transoesophageal imaging provides more accurate anatomical evaluation, although the effects of sedation on blood pressure may alter LV loading conditions and result in underestimation of severity. Since SMR is a dynamic condition, stress echocardiography allows



**Figure 1** The pathophysiology of secondary mitral regurgitation (SMR). Primary disease of the left ventricular (LV) myocardium or damage secondary to ischaemic heart disease results in papillary muscle displacement, leaflet tethering, annular remodelling, and dilatation. Compensatory mechanisms of adaptive leaflet growth are typically insufficient (and frequently accompanied by maladaptive leaflet thickening and fibrosis),<sup>14</sup> resulting in failure of leaflet coaptation. Dynamic factors affecting LV preload (e.g. hydration status, medication) and afterload (e.g. blood pressure, exercise, medication) impact on the severity of resulting SMR. Progressive LV dilatation begets increasing SMR and the resulting increase in regurgitant fraction (with corresponding reduction in forward flow) impacts negatively on the Frank–Starling curve. Adapted with permission from Mullens and Martens.<sup>15</sup> EMT, epithelial-mesenchymal transition; HF, heart failure; LV, left ventricle; LA, left atrium; MR, mitral regurgitation; PM, papillary muscle; TGF-β, transforming growth factor beta.

assessment of its role during exercise (and possibly acute HF), as well as haemodynamic assessment of the interaction between MR severity and LV function,<sup>26,27</sup> but its precise role remains unclear. Multi-detector computed tomography provides detailed anatomical information and is valuable in planning specific mitral interventions.<sup>28,29</sup> Cardiac magnetic resonance allows precise measurement of LV volume and ejection fraction, identification of fibrosis or scar, and accurate quantification of MR severity, though its availability and use in clinical practice are limited.<sup>30</sup>

### Anatomical assessment

Determination of the precise mechanism of MR [using three-dimensional (3D) transthoracic and transoesophageal echocardiography if necessary] is essential to define the optimal treatment strategy. Although several aetiologies may coexist in an individual patient, the predominant mechanism should be identified to distinguish between those with primary MR and reduced LV function and those with true SMR.

Key anatomical features are as follows (Figure 2):



- **Mitral valve:** degree of leaflet tethering, tenting area, coaptation depth, jet location (central vs. commissural), presence or absence of leaflet calcification, angle between the posterior leaflet and annular plane, posterior leaflet length, and valve area (ideally  $>5$  mm and  $\geq 4$  cm<sup>2</sup> for edge-to-edge repair, respectively).
- **Left ventricle:** end-diastolic and end-systolic diameters and volumes, LVEF, LV dyssynchrony, sphericity index (long/short LV axis), inter-papillary muscle distance, regional wall motion abnormalities.
- **Other structures:** left atrial volume, left atrial appendage (to exclude thrombus), right ventricular dimensions and function, concomitant tricuspid regurgitation, estimated pulmonary artery pressure.

## Echocardiographic assessment of secondary mitral regurgitation severity

Severity of SMR should be assessed using an integrated multi-parametric approach.<sup>31,32</sup> Two-dimensional transthoracic echocardiography has specific limitations in the setting of SMR and 3D imaging should be used whenever feasible. Importantly, SMR is a dynamic phenomenon and severity may vary significantly according to loading conditions<sup>33</sup>—assessment should be undertaken in stable clinical conditions (controlled blood pressure, optimal medical therapy), and interpreted cautiously in decompensated patients (fluid overload, inotropic support).

Definitions vary in Europe and the USA (Table 1)<sup>11,34,35</sup> and this discordance is of pivotal importance when considering the differing inclusion criteria of clinical trials. European guidelines define severe SMR as an EROA  $\geq 20$  mm<sup>2</sup> or regurgitant volume  $\geq 30$  mL, based upon adverse outcomes in observational studies using these specific thresholds.<sup>23,26,36</sup> However, quantitative assessment is highly operator-dependent with limited reproducibility, inaccurate in the presence of an elliptical regurgitant orifice (observed frequently in SMR) or multiple jets, and often overlooked in everyday clinical practice. To mitigate the risk of error, multiple parameters should be assessed [vena contracta, pulmonary vein systolic flow reversal, proximal isovelocity surface area (PISA) radius, and the subsequently derived EROA and regurgitant volume],<sup>11,35</sup> including 3D imaging (3D vena contracta area) if there is persisting diagnostic uncertainty.<sup>37,38</sup>

## Management

### The Heart Team

Heart failure is characterized by multiple cardiovascular and non-cardiovascular comorbidities and management of individual patients is frequently complex. Pharmacological, surgical, device, and transcatheter treatment options (and criteria for their optimal use) are constantly evolving.<sup>39</sup> Multidisciplinary management of HF is strongly recommended in the ESC guidelines (Class IC)<sup>10,40</sup> to achieve the best mode, sequence, and timing of treatment tailored to the needs of an individual patient. Although unsupported by a robust evidence base, the advantages of Heart Team management and decision-making have already been demonstrated in patients with complex coronary and VHD.<sup>11,41</sup> In the HF setting, the Heart Team should include an HF specialist, a cardiovascular imaging specialist, a cardiac electrophysiologist, an interventional cardiologist with expertise in transcatheter mitral valve intervention, and a cardiac surgeon with

experience in mitral valve surgery. According to local institutional circumstances, this team should meet regularly, in particular to discuss patients with complex clinical and anatomical characteristics.

### Pharmacological therapy

Optimization of GDMT is the first essential step in management of symptomatic moderate or severe SMR.<sup>10</sup> Neurohormonal inhibitors, including angiotensin-converting enzyme inhibitors (ACEi), angiotensin receptor blockers (ARB), beta-blockers, and mineralocorticoid receptor antagonists are mandatory in patients with HFrEF unless contraindicated or intolerable, and should be titrated to the guideline-directed dose (or maximum tolerated). These agents attenuate LV dysfunction and remodelling,<sup>42,43</sup> while some studies show that ACEi and beta-blockers may reduce SMR whilst improving LV geometry and function (although evidence remains inconclusive).<sup>44,45</sup>

Further pharmacological options in patients who remain symptomatic include ivabradine (if sinus rhythm is maintained with heart rate  $\geq 70$  b.p.m. despite beta-blockade, or if beta-blockers are not tolerated) and replacement of ACEi or ARB with sacubitril/valsartan.<sup>10</sup> In the PRIME study enrolling patients with HF and SMR, sacubitril/valsartan induced a significant reduction of EROA and regurgitant volume at 1 year follow-up on top of standard medical therapy (without inducing hypotension or other adverse events).<sup>46</sup> Diuretics, nitrates, and hydralazine also reduce LV preload and afterload and are associated with symptomatic improvement in patients with SMR.<sup>18,47</sup>

Oral anticoagulation is essential in patients with AF and SMR. Alternative therapeutic approaches focused on rhythm and rate control (including catheter ablation) may reduce the severity of 'atrial' MR<sup>22,48</sup> but are beyond the scope of this position statement.

### Cardiac resynchronization therapy

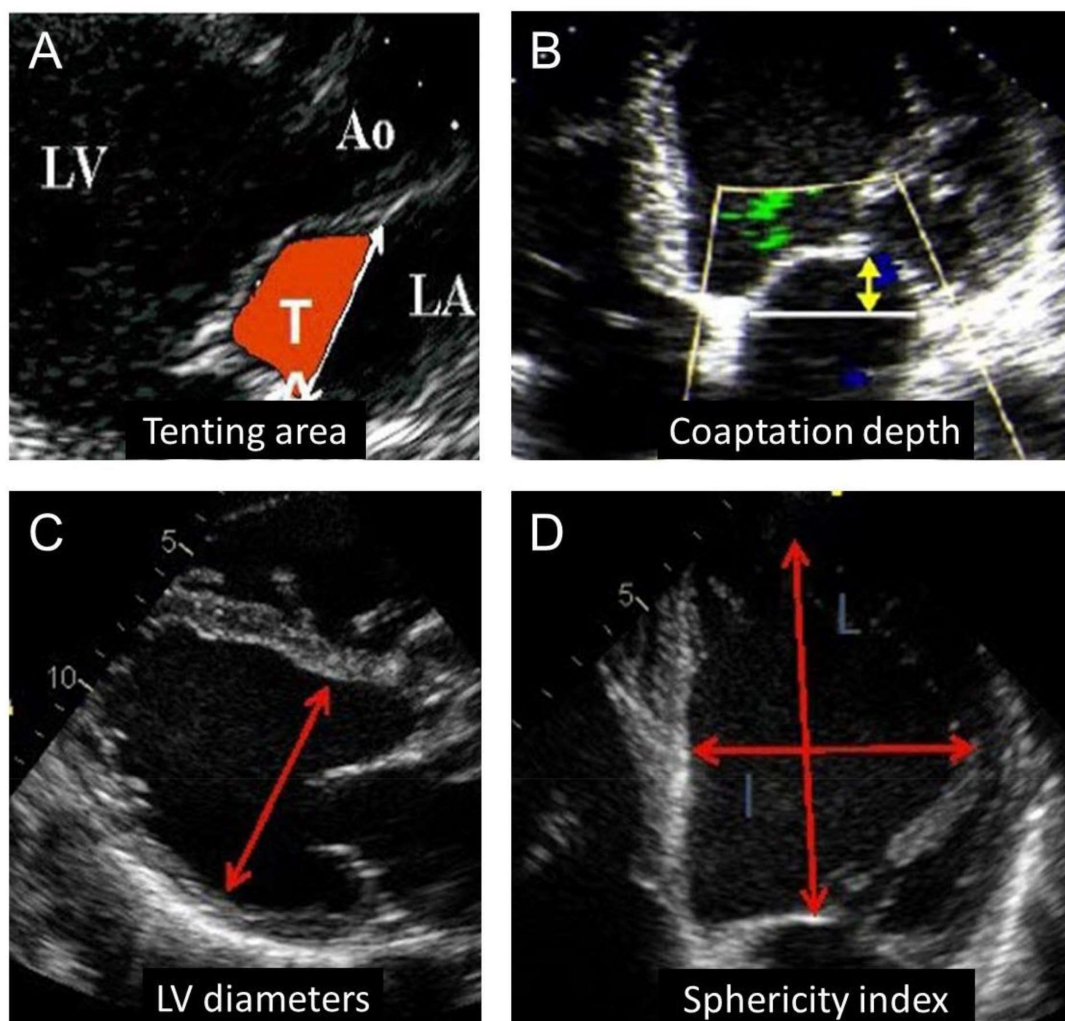
Intraventricular dyssynchrony may itself precipitate SMR via various mechanisms.<sup>49</sup> Although no prospective randomized clinical trials have investigated cardiac resynchronization therapy (CRT) in the setting of severe MR, CRT improves global LV function, attenuates LV remodelling, and reduces papillary muscle dyssynchrony in patients with QRS prolongation, thereby reducing SMR by increasing mitral valve closing forces and reducing leaflet tethering both at rest and during exercise.

Large randomized trials have confirmed short- and long-term reduction of MR (assumed to be of secondary origin in the majority of patients) following CRT implantation<sup>50</sup> as a result of reverse remodelling,<sup>51,52</sup> although the magnitude of this reduction is modest (20–35% using different quantification methods). Short-term reduction in MR after CRT implantation predicts a favourable clinical response,<sup>53</sup> whereas persistent MR is associated with reduced survival.<sup>54,55</sup>

### Coronary revascularization

Although the merits of surgical revascularization in HF have been well investigated,<sup>56</sup> there are only limited data demonstrating a lower incidence of cardiovascular adverse events compared with medical therapy in patients with SMR.<sup>57–59</sup> Following isolated CABG, MR improves in about 50% of patients.<sup>60,61</sup>

Data concerning the effects of percutaneous coronary intervention in SMR are limited. Reduction of MR was observed in about one-third of the patients in one small study and linked to better survival.<sup>62</sup>



**Figure 2** Key echocardiographic data in secondary mitral regurgitation concerning the mitral valve (A, B) and left ventricle (C, D). (A) The tenting area (highlighted in red) is bound by the anterior and posterior leaflets and the mitral annular plane (white arrow). (B) Coaptation depth represents the distance from the annular plane of the mitral valve to the leaflet coaptation point (yellow arrow). (C) The LV diameter (red arrow) must be measured in end-diastole and end-systole. (D) Sphericity index is the ratio between the measured end-diastolic volume (EDV) and a spherical volume based on the longitudinal dimension of the left ventricle. Ao, aorta; LA, left atrium; LV, left ventricle; T, tenting area.

The extent and distribution of myocardial perfusion defects appear to predict clinical response.<sup>63</sup>

## Surgery

Current ESC/EACTS guidelines provide consensus recommendations for mitral valve surgery in patients with (i) severe SMR and LVEF >30% who are undergoing CABG (Class I Level C), (ii) symptomatic severe SMR and LVEF <30% with evidence of myocardial viability and revascularization options (Class IIa Level C), and (iii) symptomatic severe SMR and LVEF >30% but unsuitable for revascularization (Class IIb Level C).<sup>11</sup> However, it is important to emphasize that these recommendations were made before the availability of robust data supporting the potential benefits of transcatheter valve repair techniques.

The evidence supporting surgical intervention for SMR remains weak. Mitral annuloplasty, the most commonly used technique for surgical mitral valve repair, reduces MR, improves symptoms, and results in reverse LV remodelling in the short term.<sup>64</sup> It remains unclear whether these outcomes are durable or reduce mortality<sup>7,8</sup> although low rates of recurrent MR (28%) have been recently reported at 10-year follow-up in a single-centre study.<sup>65</sup> In a randomized controlled trial, additional surgical treatment of moderate SMR (EROA 0.2–0.39 cm<sup>2</sup>) had no beneficial clinical effect in patients undergoing surgical revascularization at 2-year follow-up.<sup>9</sup> Besides repair, chordal sparing MV replacement presents a further surgical option. In a randomized study comparing mitral valve repair and chordal sparing mitral valve replacement in patients with severe SMR, there was no significant difference in 2-year mortality (19.0% vs. 23.2%;  $P=0.39$ ) or rates of LV reverse remodelling.<sup>66</sup> Although recurrent

**Table 1** Summary of the European and US guideline definitions of severe SMR

	2017 ESC guidelines <sup>11</sup>		2017 ASE guidelines <sup>35</sup>	2020 AHA/ACC guidelines <sup>34</sup>
Semi-quantitative criteria				
Vena contracta (mm)	≥7 (>8 for biplane)		≥7	—
Pulmonary vein	Pulmonary vein systolic flow reversal		Pulmonary vein systolic flow reversal	—
Inflow	E-wave dominant ≥1.5 m/s		—	—
Other	TVI mitral/TVI aortic >1.4		Central large jet > 50% of LA area	—
Quantitative criteria				
	<b>Primary</b>	<b>Secondary</b>		
EROA (mm <sup>2</sup> )	≥40	≥20	≥40 (or 30–39 with 3 other severity criteria or elliptical orifice)	≥40
PISA radius	—	—	≥1.0 cm at Nyquist 30–40 cm/s	—
Regurgitant volume (mL)	≥60	≥30	≥60	≥60
Regurgitant fraction (%)	—	—	≥50	≥50

ACC, American College of Cardiology; AHA, American Heart Association; ASE, American Society of Echocardiography; EROA, effective regurgitant orifice area; ESC, European Society of Cardiology; LA, left atrium; PISA, proximal isovelocity surface area; TVI, time velocity integrals.

MR was more frequent in the repair group (58.8% vs. 3.8%,  $P < 0.001$ ) resulting in a higher rate of cardiovascular re-hospitalization (48.3 vs. 32.2 per 100 patient-years,  $P = 0.01$ ), patients in the repair group without recurrent MR demonstrated significant reverse remodelling. In the absence of effective surgical approaches to the ventricular aspect of SMR, novel repair techniques that may reduce MR more effectively by combining subannular reconstruction (e.g. papillary muscle relocation) or leaflet augmentation with standard annuloplasty require further evaluation.<sup>67</sup>

Overall, however, isolated valve surgery is rarely performed for SMR in real-world clinical practice due to the high procedural risk and inconsistent evidence of clinical benefit.<sup>68</sup> Patients with advanced HF and severe SMR may be better served by cardiac transplantation or LV assist device implantation (either as destination therapy or a bridge to transplantation).

### Transcatheter mitral valve repair

The 2017 ESC guidelines for the management of VHD provide a Class IIb Level C recommendation for the use of transcatheter edge-to-edge repair in patients with SMR and impaired LV function who remain symptomatic despite optimal medical therapy<sup>11</sup> but do not incorporate insights from recent randomized controlled trials investigating the role of transcatheter techniques in this patient group.

As a result of large-scale clinical experience (>100 000 patients) and high levels of patient safety, MitraClip has become the first-line interventional treatment option for SMR in Europe. Clinical improvement (change of NYHA class, increased 6-min walking distance and reverse LV remodelling)<sup>69–72</sup> and improved survival<sup>73–75</sup> have been reported after transcatheter mitral edge-to-edge repair in several observational studies. Predictors of poor outcome have also been identified: advanced HF (NYHA class IV), severe reduction in LVEF (<30%), very high EROA (>70 mm<sup>2</sup>), extremely high NT-proBNP values (>10 000 pg/mL), significant right ventricular dysfunction (tricuspid annular plane systolic excursion <15 mm), severe pulmonary

hypertension or tricuspid regurgitation, and the presence of major comorbidities (such as significant renal dysfunction).<sup>71,72,76,77</sup>

Two recent randomized controlled trials from France and the USA/Canada have evaluated the safety and efficacy of MitraClip implantation in patients with symptomatic HF and moderate-severe SMR despite medical therapy (Table 2).

In the French multicentre Percutaneous Repair with the MITRA-FR trial,<sup>13</sup> 304 patients with symptomatic HF (NYHA class II–IV), LVEF of 15–40% (but no limit of end-systolic dimension), a history of at least one HF hospitalization within 1 year and severe SMR (defined as EROA >20 mm<sup>2</sup> or regurgitant volume >30 mL) but unsuitable for surgery were randomized to undergo MitraClip implantation plus GDMT or GDMT alone. MitraClip implantation had no impact on the primary endpoint of all-cause mortality or HF hospitalization at 12 months compared with GDMT alone (HR 1.16, 95% CI 0.73–1.84) and no additional effect on functional status, 6-min walking distance, quality of life, or LV end-diastolic volumes (although incomplete assessment of these secondary outcome measures hampered meaningful statistical analysis). Recently reported extended observations showed no change in these findings at 24-month follow-up, with no impact of MitraClip implantation on all-cause mortality or HF hospitalization.<sup>79</sup>

In the Cardiovascular Outcomes Assessment of the MitraClip Percutaneous Therapy for Heart Failure Patients with Functional Mitral Regurgitation (COAPT) trial,<sup>12</sup> 614 patients with symptomatic HF (NYHA class II, III, or ambulatory IV), LVEF 20–50%, LV end-systolic diameter ≤70 mm, at least one HF hospitalization within the previous year or increased natriuretic peptide levels, with moderate-to-severe or severe SMR (semi-quantitative grade 3+ or 4+ according to integrative assessment based on American Society of Echocardiography recommendations)<sup>35,80</sup> and in whom surgery was not considered the standard of care were randomized to undergo MitraClip implantation plus optimal GDMT or optimal GDMT alone. MitraClip implantation substantially reduced the primary endpoint (hospitalization for HF, 35.8% vs. 67.9% per patient-year: HR 0.53,

**Table 2** Key differences between the COAPT and MITRA-FR trials (modified from Praz *et al.*<sup>78</sup>)

	MITRA-FR	COAPT
<b>Primary endpoint</b>	All-cause death and hospitalization for HF at 12 months	All hospitalizations for HF within 24 months (including recurrent events)
Key exclusion criteria		
Heart failure severity	NYHA class < II	NYHA class < II ACC/AHA stage D HF
Left ventricular dimensions	No exclusion criteria	LVESD >70 mm
Coronary artery disease	CABG or PCI performed within 1 month	Untreated coronary artery disease requiring revascularization
Right ventricle	No exclusion criteria	Right-sided HF with moderate or severe right ventricular dysfunction Tricuspid valve disease requiring surgery
Pulmonary disease	No exclusion criteria	COPD with home oxygen therapy or chronic oral steroid use PAP >70 mmHg unresponsive to vasodilator therapy
Principal baseline characteristics		
Number of patients screened	450	1576
Number of patients enrolled (ITT)	304	614
Mean age (years)	70 ± 10	72 ± 12
Mean LVEF (%)	33 ± 7	31 ± 10
MR severity (EROA, cm <sup>2</sup> )	0.31 ± 0.10	0.41 ± 0.15
<30 mm <sup>2</sup> (%)	52%	13%
30–40 mm <sup>2</sup> (%)	32%	46%
>40 mm <sup>2</sup>	16%	41%
Mean indexed LVEDV, mL/m <sup>2</sup>	135 ± 35	101 ± 34
Safety and efficacy endpoints in intervention arm		
Complications <sup>a</sup> (%)	14.6	8.5
No implant (%)	9	5
Implantation of multiple clips (%)	54	62
Post-procedural MR grade ≤2+ (%)	92	95
MR grade ≤2+ at 1 year (%)	83	95
Hospitalization for HF at 1 year (%)		
Edge-to-edge repair + GDMT	49	36
GDMT alone	47	68
Thirty-day mortality (%)		
Edge-to-edge repair + GDMT	3	2
GDMT alone	3	1
One-year mortality (%)		
Edge-to-edge repair + GDMT	24	19
GDMT alone	22	23
Two-year mortality (%)		
Edge-to-edge repair + GDMT	34	29
GDMT alone	35	46

BNP, brain natriuretic peptide; COPD, chronic obstructive pulmonary disease; EROA, effective regurgitant orifice area; GDMT, guideline-directed medical treatment; HF, heart failure; ITT, intention to treat; LVEF, left ventricular ejection fraction; LVESD, left ventricular end-systolic diameter; MR, mitral regurgitation; NT-proBNP, N-terminal pro brain natriuretic peptide; PAP, pulmonary artery pressure.

<sup>a</sup>Device implant failure, transfusion, or vascular complication requiring surgery, ASD, cardiogenic shock, cardiac embolism/stroke, tamponade, and urgent cardiac surgery.

95% CI 0.40–0.70,  $P < 0.001$ ; NNT 3.1, 95% CI 1.9–7.9) and every 1 of 10 pre-specified, statistically powered secondary endpoints [including 2-year all-cause mortality (29.1% vs. 46.1%: HR 0.62, 95% CI 0.46–0.82,  $P < 0.001$ ; NNT 5.9, 95% CI 3.9–11.7), the composite of death and HF re-hospitalization (45.7% vs. 67.9%: HR 0.57, 95% CI

0.45–0.71,  $P < 0.001$ ; NNT 4.5, 95% CI 3.3–7.2), symptomatic status (NYHA class I/II 72.2% vs. 49.6%;  $P < 0.001$ ), change in quality of life (Kansas City Cardiomyopathy Questionnaire score  $+12.5 \pm 1.8$  vs.  $-3.6 \pm 1.9$  points; HR 16.1, 95% CI 11.0–21.2;  $P < 0.001$ ), and 6-min walking distance ( $-2.2 \pm 9.1$  vs.  $-60.2 \pm 9.0$  m; HR: 57.9, 95% CI 32.7–



**Table 3** Randomized trials of transcatheter mitral valve repair in patients with heart failure and secondary mitral regurgitation

Study acronym	HF status	LV status	SMR severity	N	Intervention	Primary endpoint	Hazard ratio
MITRA-FR <sup>13</sup>	II-IV and HF hospitalization within 12 months	LVEF 15–40%	EROA >20 mm <sup>2</sup> and/or Rvol >30 mL, unsuitable for mitral valve surgery	304	MitraClip vs. GDMT	Death HF hospitalization at 12 months	1.16 (0.73–1.84)
COAPT <sup>12</sup>	II-IV and HF hospitalization within 12 months or elevated NPs	LVEF 20–50% LVESD ≤70 mm	Grade 3+ or 4+ Surgery not an option	614	MitraClip vs. GDMT	Cumulative HF hospitalization at 24 months	0.53 (0.40–0.70)
RESHAPE-HF2 (Ongoing)	II-IV and HF hospitalization within 12 months or elevated NPs	LVEF 15–45% (NYHA III/IV) or LVEF 15–35% (NYHA II)	Moderate-severe or severe MR EROA ≥30 mm <sup>2</sup>	650 (revised plan)	MitraClip vs. GDMT	Cardiovascular death and recurrent HF hospitalization during follow-up	—

EROA, effective regurgitant orifice area; GDMT, guideline-directed medical therapy; HF, heart failure.; LV, left ventricular; LVEF, left ventricular ejection fraction; LVESD, left ventricular end-systolic diameter; NPs, natriuretic peptides; NYHA, New York Heart Association class; Rvol, regurgitant volume; SMR, secondary mitral regurgitation.

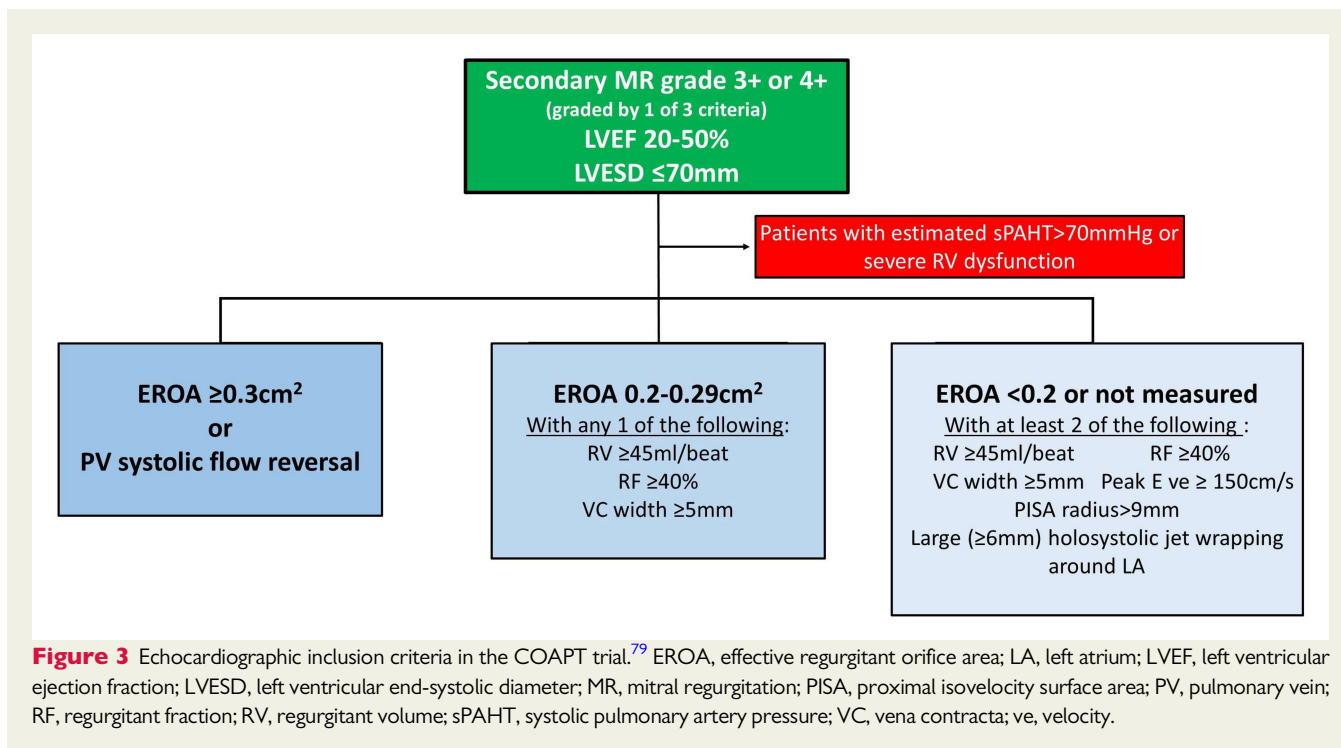
83.1,  $P < 0.001$ ), and the need for LV assist device implantation or heart transplantation during the study period (4.4% vs. 9.5%; HR 0.37, 95% CI 0.17–0.81,  $P = 0.01$ ). These benefits were even more pronounced at 3-year follow-up [composite endpoint of death and HF re-hospitalization 58.8% vs. 88.1%, HR 0.48 (95% CI 0.39–0.59),  $P < 0.001$ ; NNT 3.4 (95% CI 2.7–4.6)].<sup>81</sup> Cost-effectiveness analysis at 2 years confirmed a higher cost of intervention overall (\$73 416 vs. \$38 345,  $P < 0.001$ ; predominantly related to the price of the MitraClip device) despite the increased cost of follow-up in the GDMT group (\$38 345 vs. \$26 654;  $P = 0.018$ ), and acceptable economic value based on current US thresholds (incremental cost-effectiveness ratio \$40 361 per life-year gained, \$55 600 per quality-adjusted life-year gained).<sup>82</sup>

Whilst these two trials appear superficially similar in design, a number of differences between them may partly explain their diverging results:

- **Patient selection:** In MITRA-FR, local investigators determined eligibility, while in COAPT, this was confirmed by a central eligibility committee.
- **Medical therapy:** In COAPT, a central eligibility committee directed up-titration of medical therapy to maximally tolerated doses prior to randomization. Patients were excluded from the trial if their symptoms subsided or MR decreased as a consequence. Subsequent modification of medical treatment was discouraged in both groups. Conversely in MITRA-FR, up-titration of medical therapy before randomization was directed by the local Heart Team and constantly adapted to clinical circumstances after randomization in both groups, consistent with real-world practice.

Therefore, use of ACEi and ARB, and intensification of drug treatment (particularly beta-blockers) during follow-up was more frequent in the MitraClip group in COAPT, although the absolute impact of these differences on outcomes remains uncertain. The use of sacubitril/valsartan was low in both trials. Overall, these differences suggest that the COAPT trial enrolled more patients refractory to current evidence-based medical treatment than MITRA-FR.

- **Echocardiographic assessment:** Important differences in the severity of SMR, degree of LV dilatation, and accompanying parameters of right heart function are summarized in Table 2. Reflecting the echocardiographic trial inclusion criteria (Figure 3), patients in COAPT demonstrated greater severity of SMR based upon quantitative criteria (EROA  $41 \pm 15$  mm<sup>2</sup> vs.  $31 \pm 10$  mm<sup>2</sup>) and less LV dilatation (mean indexed LV end-diastolic volume  $101 \pm 34$  mL/m<sup>2</sup> vs.  $135 \pm 35$  mL/m<sup>2</sup>) than those enrolled in MITRA-FR. Perhaps reflecting greater severity of MR in relation to LV dimensions, patients in COAPT were overall more likely to benefit from transcatheter edge-to-edge repair in terms of reduced mortality and need for HF hospitalization<sup>20</sup> (although improvements in quality of life appeared to be independent of these parameters).<sup>83</sup> Importantly, no single echocardiographic variable (whether prognostic or not) was able to predict the outcomes observed following MitraClip implantation in the COAPT trial.<sup>60</sup> In summary, echocardiographic assessment was undertaken using different parameters in the two studies—hence, only very limited conclusions can be drawn at this stage and composite assessment of both datasets by a single independent core laboratory may prove valuable.
- **Technical factors:** The results of MITRA-FR and COAPT indicate that transcatheter mitral edge-to-edge repair using the MitraClip



device is a safe procedure that effectively reduces SMR. However, procedural differences (particularly the more frequent use of multiple clips) may explain the better long-term reduction of SMR in COAPT with impact on overall clinical outcomes (notwithstanding the different systems for grading MR in the two trials). Arguably, these differences in technical outcomes are more relevant than differences in medical therapy and highlight the importance of achieving the best possible immediate result after MitraClip implantation.

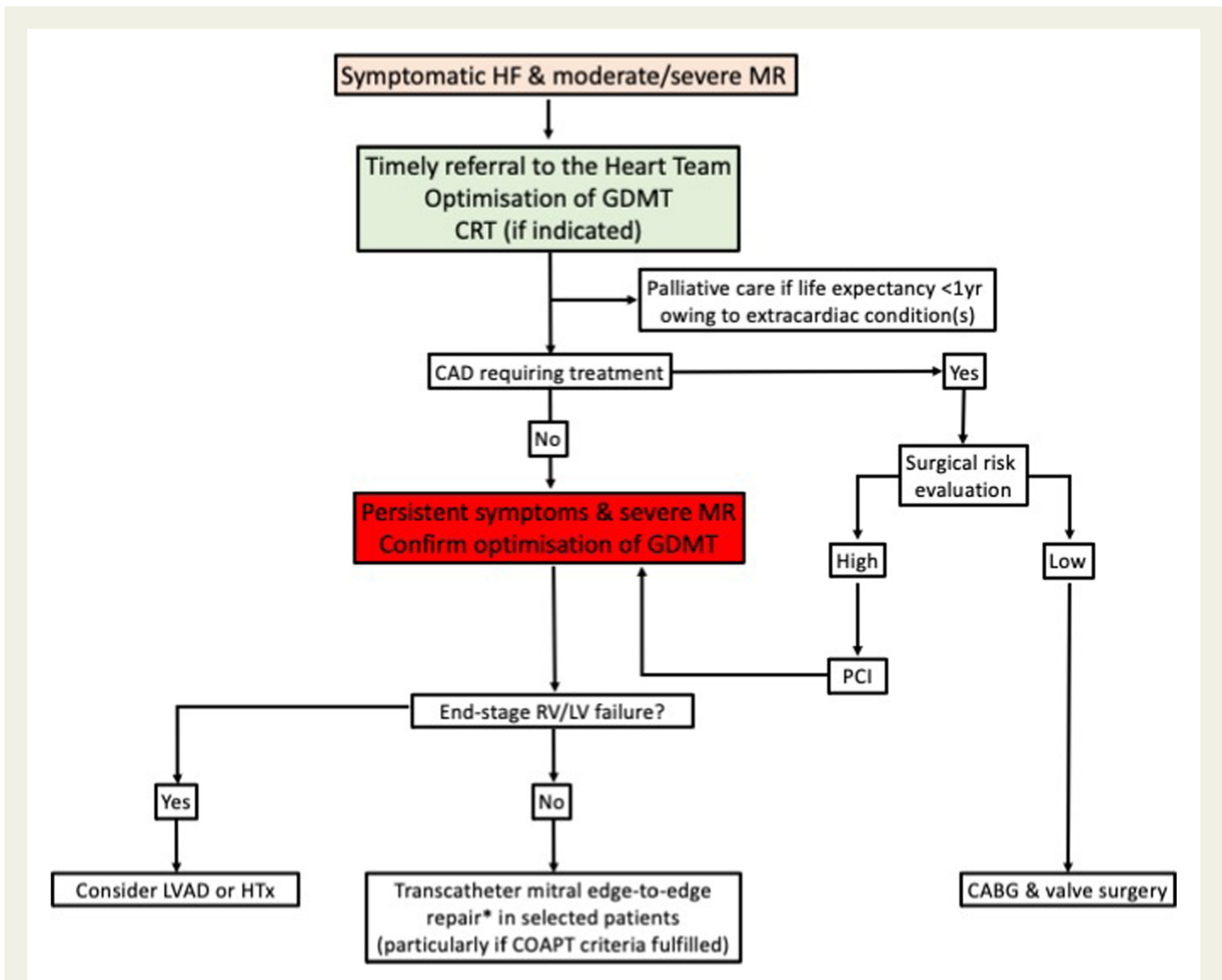
The fact that differences in clinical characteristics, advanced echocardiographic findings and initial use of medical therapy are likely to have accounted for the diverging trial outcomes further emphasizes the critical importance of careful patient selection for transcatheter mitral valve intervention by a Heart Team (see Executive Summary section). The ongoing RESHAPE-HF2 trial will randomize 650 (according to the revised plan) patients with symptomatic HF (NYHA class II, III or ambulatory IV), LVEF 15–45%, a history of at least one HF hospitalization within the previous year or increased natriuretic peptide levels, and moderate-severe or severe SMR (EROA  $\geq 30$  mm<sup>2</sup>) to MitraClip implantation plus GDMT or GDMT alone (Table 3). The primary endpoint is cardiovascular death or recurrent HF hospitalization and results are expected in 2022. Meanwhile, the MATTERHORN trial (ClinicalTrials.gov, NCT02371512) is comparing the merits of transcatheter edge-to-edge repair with surgery in patients at high-surgical risk with LVEF  $\geq 20\%$ . The results of these and future trials, combined with ongoing analyses of the MITRA-FR and COAPT databases to identify responders to edge-to-edge repair, are urgently needed to refine algorithms that ensure selection of the right patients by the right clinicians for transcatheter treatment of SMR with the right device at the right time (Figure 4).

## Futility and end-of-life care

Expensive, high-risk and ultimately futile procedures should be avoided in patients who are expected to derive little symptomatic benefit or improvement in quality of life. Examples include those with very limited life expectancy (<1 year) due to extra-cardiac conditions, severe right ventricular impairment or pulmonary disease, impaired mobility as a result of neurological or musculoskeletal disease, or advanced dementia. Specialist palliative care should be available for these patients.

## Open questions

The findings of the COAPT trial confirm the prognostic and symptomatic impact of SMR in HF patients. Although longer-term follow-up is essential, the diverging results of MITRA-FR and COAPT place even greater emphasis on the need for careful selection of patients for transcatheter repair techniques and identification of improved imaging parameters (including thresholds of MR severity) that will predict positive clinical outcomes. A greater relative degree of SMR in relation to LV dimensions may identify patients who are more likely to benefit from intervention and this concept warrants further investigation in future studies incorporating sophisticated imaging techniques (advanced echocardiography—including 3D imaging—and cardiac magnetic resonance).<sup>20</sup> Furthermore, better characterization and stratification of the SMR population may allow distinction between those patients who may obtain prognostic benefit and those who will derive symptom relief and reduced need for hospitalization alone. In practice, this may not be simple—no single echocardiographic variable predicted beneficial outcomes in the COAPT trial<sup>80</sup> and patient-level analysis of the MITRA-FR trial failed to identify any



**Figure 4** A practical algorithm for the management of secondary mitral regurgitation. Heart Team: HF specialist, cardiovascular imaging specialist, interventional cardiologist with expertise in transcatheter mitral valve repair, cardiac electrophysiologist, and cardiac surgeon with experience in mitral valve surgery. CABG, coronary artery bypass grafting; CAD, coronary artery disease; CRT, cardiac resynchronization therapy (with or without defibrillator); GDMT, guideline-directed medical therapy; HF, heart failure; HTx, heart transplantation; LV, left ventricular; LVAD, left ventricular assist device; MR, mitral regurgitation; PCI, percutaneous coronary intervention; RV, right ventricular; yr, year. \*Current studies have established the safety and effectiveness of the MitraClip for this purpose—ongoing studies will determine whether other edge-to-edge mitral repair devices are as safe and effective.

combination of echocardiographic parameters associated with clinical benefit following intervention (including those with disproportionate MR).<sup>84</sup> Sub-studies from the COAPT trial showed that symptomatic and prognostic improvements were observed irrespective of NYHA class, exercise capacity, and the presence of CRT at baseline.<sup>85–87</sup>

Transcatheter mitral valve repair for SMR is a rapidly evolving field. Beyond the MitraClip device, other percutaneous techniques are now approved for commercial use in Europe: indirect annuloplasty using the Carillon Mitral Contour System (Cardiac Dimensions, Kirkland, WA, USA),<sup>88</sup> direct annuloplasty using the Cardioband Mitral System (Edwards Lifesciences, Irvine, CA, USA),<sup>89</sup> and edge-to-edge repair using the PASCAL Mitral Valve Repair System (Edwards Lifesciences, Irvine, CA, USA).<sup>90,91</sup> The Carillon system has

been recently investigated in a randomized sham-controlled study (REDUCE-FMR) enrolling 120 patients receiving GDMT.<sup>88</sup> At 12 months, indirect annuloplasty using this system was associated with a significant 22% fall in MR regurgitant volume (the primary endpoint) accompanied by significant reduction in LV volumes and improvement in paired 6-min walking distance and NYHA functional class. However, the trial was not powered for clinical endpoints and between-group differences (including the incidence of mortality or HF re-hospitalization) did not differ significantly.

Since the safety and utility of MitraClip have now been proven in selected patients, the potential for intervention earlier in the natural history of the disease to prevent irreversible LV remodelling and systolic impairment will need to be rigorously evaluated in future studies. Further research is also needed for specific populations

## Executive summary

### The Management of Secondary Mitral Regurgitation in Heart Failure

- Secondary mitral regurgitation (SMR) is a common consequence of left ventricular remodelling and associated with adverse prognosis.
- Severity of SMR should be assessed by experienced echocardiographers using an integrated multi-parametric approach.
- Patients with symptomatic heart failure (HF) and moderate or severe SMR should be referred in a timely manner to a multidisciplinary Heart Team, including:
  - Heart failure specialist
  - Cardiovascular imaging specialist
  - Interventional cardiologist with expertise in transcatheter mitral valve repair
  - Cardiac electrophysiologist
  - Cardiac surgeon with experience in mitral valve surgery
- The Heart Team should first evaluate and optimize guideline-directed medical therapy (GDMT) and then consider the respective roles of device therapy (including cardiac resynchronization therapy, CRT), transcatheter mitral intervention and surgery (mitral repair, ventricular assist systems or transplantation), and their order of implementation.
- Decisions concerning treatments for mitral regurgitation, other than pharmacological therapy or circulatory support, should ideally be made in stable patients without fluid overload or the need for inotropic support.
- Surgical treatment of severe SMR should be considered in operable patients with coronary artery disease requiring surgical revascularization.
- Transcatheter edge-to-edge repair\* is an evidence-based treatment option in patients with severe SMR who remain symptomatic despite GDMT (including CRT when indicated) and who have been carefully selected by a multidisciplinary Heart Team.
- Circulatory support devices and cardiac transplantation should be considered as an alternative in patients with advanced left and/or right ventricular failure.
- Interventions for mitral regurgitation should be avoided in patients with life expectancy <1 year due to conditions unrelated to the mitral regurgitation.

\*Current studies have established the safety and effectiveness of the MitraClip for this purpose—ongoing studies will determine whether other edge-to-edge mitral repair devices are as safe and effective.

overlooked in recent studies, including those with advanced HF (excluded from COAPT) or marked LV dilation and severe SMR (EROA  $\geq 30$  mm<sup>2</sup>, under-represented in MITRA-FR). Integrative approaches combining the benefits of pharmacological, electrophysiological, and transcatheter valve interventions and their relative priority in individual patients will ultimately determine the optimal management of SMR in HF.

Finally, and perhaps most importantly, timely assessment and management of SMR remain suboptimal.<sup>89</sup> Robust diagnostic criteria, earlier referral for specialist assessment and stricter evidence-based selection criteria will increase the net benefit of transcatheter valve and other advanced interventions.<sup>92–95</sup> These priorities need to be addressed urgently alongside improved education and training of the wider cardiovascular community—only then will outcomes for the high-risk group of patients with SMR and HF improve significantly.

## Conclusions

SMR affects a large proportion of patients with HF and is independently associated with adverse prognosis. Timely diagnosis is therefore essential and requires high-quality imaging delivered by trained imaging specialists to appropriately define the severity and mechanism(s) of MR, and predict the potential response to treatment. Management is complex and these patients should be referred for timely Heart Team assessment and management. Medical therapy should be optimized and adjusted meticulously over long-term follow-up in all patients with SMR and HF, supplemented by CRT according to guideline recommendations. The COAPT trial provides robust evidence supporting the use of transcatheter mitral edge-to-edge repair using the MitraClip device in patients who remain symptomatic despite these measures and match the trial inclusion criteria. Given that these findings were not duplicated in the MITRA-FR trial, however, further data will be needed to refine optimal patient selection criteria. Heart Teams may also consider the use of transcatheter mitral edge-to-edge repair for symptomatic improvement in patients who do not match these criteria if alternative treatments (including LV assist device therapy or heart transplantation) are inappropriate or unavailable. Whilst international guidelines should be updated to reflect the findings of the recent randomized trials, further high-quality studies are required to refine selection criteria, explore indications beyond the current evidence base, and investigate the role of other transcatheter treatment options (annuloplasty, combined repair techniques, valve replacement).

**Conflict of interest:** A.J.S.C.: Related to the present work: None. Outside the submitted work—grants and personal fees from Vifor Int, personal fees from AstraZeneca, Bayer, Boehringer Ingelheim, Menarini, Novartis, Nutricia, Servier, Vifor, Abbott, Actimed, Arena, Cardiac Dimensions, Corvia, CVRx, Enopace, ESN Cleer, Faraday, Gore, Impulse Dynamics, and Respicardia. S.D.A.: Related to the present work: None. Outside the submitted work—grants and personal fees from Vifor Int and Abbott Vascular, personal fees from Bayer, Boehringer Ingelheim, Novartis, Servier, Impulse Dynamics, Cardiac Dimensions, Actimed, AstraZeneca, Amgen, Bioentrix, Janssen, Respicardia, V-Wave, and Brahms. A.B.: Related to the present work: None. Outside the submitted work—grants and personal fees from Abbott Vascular, and personal fees from Medtronic, Sinomed, Microport, KSH, and Pi-Cardia. R.S.v.B.: Related to the present work: None. Outside the submitted work—personal fees and non-financial support from Abbott Vascular, Edwards Lifesciences, Bioentrix, Cardiac Dimensions and personal fees from Philips. J.B.: Related to the present work: none. Outside the submitted work—grants and personal fees from Vifor, Bayer, CVRx, Abiomed Medtronic, grants



from Zoll, and personal fees from Novartis, BMS, Pfizer, Servier, Orion, MSD, Boehringer Ingelheim, AstraZeneca, Abbott, and Cardior. J.J.B.: Related to the present work: none. Outside the submitted work—grants from Bayer, Medtronic, Boston Scientific, Biotronik, Abbott, Edwards Lifescience, and GE Healthcare and personal fees from Abbott, Medtronic and Edwards Lifescience. S.B.: Related to the present work: None. Outside the submitted work—personal fees from Medtronic, Boston Scientific, Zoll, and Microport. J.Č.: Related to the present work: None. Outside the submitted work—personal fees from Boehringer Ingelheim, AstraZeneca, Novartis, and Sanofi. J.G.C.: Related to the present work: None. Outside the submitted work—grants and personal fees from Bayer, Bristol Myers Squibb, Vifor, Pharmacosmos, Cytokinetics, Johnson & Johnson, Myokardia, Stealth Biopharmaceuticals, and Viscardia, and personal fees from Abbott, Amgen, Novartis, Medtronic, Idorsia, Servier, Boehringer Ingelheim, AstraZeneca, Innolife, Torrent, grants and Respicardia. T.D.: Related to the present work: none. Outside the submitted work—personal fees from Biotonik, Abbott, and Boston Scientific. D.F.: Related to the present work: None. Outside the submitted work—personal fees from Abbott Laboratories, Bayer, Boehringer Ingelheim, Leo, Menarini, Novartis, Orion Pharma, and Roche Diagnostics. G.F.: Related to the present work: None. Outside the submitted work—Committee member in trials/registries sponsored by Medtronic, Vifor, Novartis, Bayer, Boehringer Ingelheim, and Servier and personal fees from Servier, Novartis, and Boehringer Ingelheim. J.H.: Related to the present work: None. Outside the submitted work—grants and personal fees from Abbott Vascular and Edwards Lifesciences. E.A.J.: Related to the present work: None. Outside the submitted work—grants and personal fees from Vifor Pharma and personal fees from Abbott, Novartis, Servier, Boehringer Ingelheim, Berlin Chemie, Pfizer, Gedeon Richter, Fresenius, Bayer, AstraZeneca, and Cardiac Dimensions. M.L.: Related to the present work: None. Outside the submitted work—grants from Roche Diagnostics and personal fees from Novartis, Boehringer Ingelheim, Vifor, and AstraZeneca. L.H.L.: Related to the present work: None. Related to the present work: None. Outside the submitted work—grants and personal fees from Relypsa, Boehringer Ingelheim, and Novartis, grants from Boston Scientific and personal fees from Merck, Vifor-Fresenius, AstraZeneca, Bayer, Pharmacosmos, Abbott, Medscape, Myokardia, Sanofi, Lexicon, and Mundipharma. M.R.M.: Related to the present work: None. Outside the submitted work—personal fees from Abbott, Medtronic, Janssen, Mesoblast, Baim Institute for Clinical Research, Portola, Bayer, Triple Gene, NupulseCV, Leviticus, and FineHeart. M.M.: Related to the present work: None. Outside the submitted work—personal fees and non-financial support from Amgen, Abbott Vascular, and Bayer and personal fees from Servier, AstraZeneca, Edwards Therapeutics, Vifor pharma, Actelion, LivaNova, and WindTree Therapeutics. N.M.: Related to the present work: grants and personal fees from Novartis and personal fees from Bayer, AstraZeneca, and a clinical research protocol with Amgen. Unrelated to the present work: None. C.Mue.: Related to the present work: none. Outside the submitted work—grants and personal fees from Novartis, and grants, personal fees and non-financial support from several diagnostic companies. C.Mun.: Related to the present work: none. Outside the submitted work—grants from LIVANOVA and personal fees from ATRICURE. J.-F.O.: Related to the present work:

none. Outside the submitted work—grants from Abbott and Carmat and personal fees from Delacroix Chevalier, Landanger, and Medtronic. P.P.: Related to the present work: none. Outside the submitted work—grants and personal fees from Vifor Pharma and personal fees from Abbott Vascular, Novartis, Servier, Boehringer Ingelheim, AstraZeneca, Pfizer, Bayer, Berlin Chemie, Impulse Dynamics, Coridea, Respicardia, Amgen, and RenalGuardSolutions. F.P.: Related to the present work: none. Outside the submitted work—travel expenses from Edwards Lifesciences, Abbott Vascular, and Polares Medical. V.R.: Related to the present work: none. Outside the submitted work—grants from Edwards Lifesciences and Abbott Vascular. F.R.: Related to the present work: none. Outside the submitted work: The Department of Cardiology (University Hospital of Zurich/University of Zurich) reports research-, educational- and/or travel grants from Abbott, Amgen, Astra Zeneca, Bayer, Berlin Heart, B. Braun, Biosense Webster, Biosensors Europe AG, Biotronik, BMS, Boehringer Ingelheim, Boston Scientific, Bracco, Cardinal Health Switzerland, Daiichi, Diatools AG, Edwards Lifesciences, Guidant Europe NV (BS), Hamilton Health Sciences, Kaneka Corporation, Labormedizinisches Zentrum, Medtronic, MSD, Mundipharma Medical Company, Novartis, Novo Nordisk, Orion, Pfizer, Quintiles Switzerland Sarl, Sanofi, Sarstedt AG, Servier, SIS Medical, SSS International Clinical Research, Terumo Deutschland, V- Wave, Vascular Medical, Vifor, Wissens Plus, ZOLL. FR has not received personal payments by pharmaceutical companies or device manufacturers in the last 3 years (remuneration for the time spent in activities, such as participation as steering committee member of clinical trials and as member of the Pfizer Research Award selection committee in Switzerland, were made directly to the University of Zurich). The research and educational grants do not impact on Prof. Ruschitzka's personal remuneration. P.M.S.: Related to the present work: none. Outside the submitted work—personal fees from Medtronic, Abbott, Servier, AstraZeneca, Respicardia, Boehringer Ingelheim, Novartis, and Vifor Pharma. A.V.: Related to the present work: Edwards Life Sciences, Medtronic, and Abbott Vascular. Outside the submitted work—personal fees from Edwards Life Sciences, Medtronic, Abbott Vascular and Cardiovalve. S.W.: Related to the present work: none. Outside the submitted work—grants from Abbott, Amgen, BMS, Bayer, Boston Scientific, Biotronik, Cardinal Health, CardioValve, CSL Behring, Daiichi Sankyo, Edwards Lifesciences, Johnson&Johnson, Medtronic, Querbet, Polares, Sanofi, Terumo, Sinomed, and service as an unpaid advisory board member and/or unpaid member of the steering/executive group of trials funded by Abbott, Abiomed, Amgen, AstraZeneca, BMS, Boston Scientific, Biotronik, Cardiovalve, Edwards Lifesciences, MedAlliance, Medtronic, Novartis, Polares, Sinomed, V-Wave, and Xeltis, but has not received personal payments by pharmaceutical companies or device manufacturers. He is also member of the steering/executive committee group of several investigator-initiated trials that receive funding by industry without impact on his personal remuneration. S.W. is an unpaid member of the Pfizer Research Award selection committee in Switzerland. J.L.Z.: Related to the present work: None. Outside the submitted work—grants from ABBOTT and EDWARDS, and personal fees from BAYER, PFIZER, and DAICHI. H.H.: Related to the present work: None. Outside the submitted work—grants and personal fees from Biotronik and Pfizer-BMS, and grants from Boston Scientific, Bayer,

Boehringer Ingelheim, and Daiichi Sankyo. B.P.: Related to the present work: None. Outside the submitted work—grants and personal fees from Edwards Lifesciences, and personal fees from Abbott and Anteris. The remaining authors report no conflict of interest.

## References

- Varadarajan P, Sharma S, Heywood JT, Pai RG. High prevalence of clinically silent severe mitral regurgitation in patients with heart failure: role for echocardiography. *J Am Soc Echocardiogr* 2006;**19**:1458–1461.
- Pu M. The frequency, impact, and management of mitral regurgitation in patients with heart failure. *Curr Cardiol Rep* 2006;**8**:226–231.
- Bursi F, Barbieri A, Grigioni F, Reggiani L, Zanasi V, Leuzzi C, Ricci C, Piovaccari G, Branzi A, Modena MG. Prognostic implications of functional mitral regurgitation according to the severity of the underlying chronic heart failure: a long-term outcome study. *Eur J Heart Fail* 2010;**12**:382–388.
- Goliasch G, Bartko PE, Pavo N, Neuhold S, Wurm R, Mascherbauer J, Lang IM, Strunk G, Hulsmann M. Refining the prognostic impact of functional mitral regurgitation in chronic heart failure. *Eur Heart J* 2018;**39**:39–46.
- Dziadzko V, Clavel MA, Dziadzko M, Medina-Inojosa JR, Michelena H, Maalouf J, Nkomo V, Thapa P, Enriquez-Sarano M. Outcome and undertreatment of mitral regurgitation: a community cohort study. *Lancet* 2018;**391**:960–969.
- Asgar AW, Mack MJ, Stone GW. Secondary mitral regurgitation in heart failure: pathophysiology, prognosis, and therapeutic considerations. *J Am Coll Cardiol* 2015;**65**:1231–1248.
- Wu AH, Aaronson KD, Bolling SF, Pagani FD, Welch K, Koelling TM. Impact of mitral valve annuloplasty on mortality risk in patients with mitral regurgitation and left ventricular systolic dysfunction. *J Am Coll Cardiol* 2005;**45**:381–387.
- Mihaljevic T, Lam BK, Rajeswaran J, Takagaki M, Lauer MS, Gillinov AM, Blackstone EH, Lytle BW. Impact of mitral valve annuloplasty combined with revascularization in patients with functional ischemic mitral regurgitation. *J Am Coll Cardiol* 2007;**49**:2191–2201.
- Michler RE, Smith PK, Parides MK, Ailawadi G, Thourani V, Moskowitz AJ, Acker M, Hung JW, Chang HL, Perrault LP, Gillinov AM, Argenziano M, Bagiella E, Overbey JR, Moquete EG, Gupta LN, Miller MA, Taddei-Peters WC, Jeffries N, Weisel RD, Rose EA, Gammie JS, DeRose JJ, Puskas JD, Dagenais F, Burks SG, El-Hamamsy I, Milano CA, Atluri P, Voisine P, O'Gara PT, Gelijs AC; CTSN. Two-year outcomes of surgical treatment of moderate ischemic mitral regurgitation. *N Engl J Med* 2016;**374**:1932–1941.
- Ponikowski P, Voors AA, Anker SD, Bueno H, Cleland JGF, Coats AJS, Falk V, Gonzalez-Juanatey JR, Harjola VP, Jankowska EA, Jessup M, Linde C, Nihoyannopoulos P, Parissis JT, Pieske B, Riley JP, Rosano GMC, Ruilope LM, Ruschitzka F, Rutten FH, van der Meer P; ESC Scientific Document Group. 2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure: the Task Force for the diagnosis and treatment of acute and chronic heart failure of the European Society of Cardiology (ESC) Developed with the special contribution of the Heart Failure Association (HFA) of the ESC. *Eur Heart J* 2016;**37**:2129–2200.
- Baumgartner H, Falk V, Bax JJ, De Bonis M, Hamm C, Holm PJ, Jung B, Lancellotti P, Lansac E, Rodriguez Muñoz D, Rosenhek R, Sjögren J, Tornos Mas P, Vahanian A, Walther T, Wendler O, Windecker S, Zamorano JL, ESC Scientific Document Group. 2017 ESC/EACTS Guidelines for the management of valvular heart disease. *Eur Heart J* 2017;**38**:2739–2791.
- Stone GW, Lindenfeld J, Abraham WT, Kar S, Lim DS, Mishell JM, Whisenant B, Grayburn PA, Rinaldi M, Kapadia SR, Rajagopal V, Sarembok IJ, Briekie A, Marx SO, Cohen DJ, Weissman NJ, Mack MJ; COAPT Investigators. Transcatheter mitral-valve repair in patients with heart failure. *N Engl J Med* 2018;**379**:2307–2318.
- Obadia JF, Messika-Zeitoun D, Leurent G, Jung B, Bonnet G, Piriou N, Lefevre T, Piot C, Rouleau F, Carrie D, Nejari M, Ohlmann P, Leclercq F, Saint Etienne C, Teiger E, Leroux L, Karam N, Michel N, Gilard M, Donal E, Trochu JN, Cormier B, Armoiry X, Boutitie F, Maucort-Boulch D, Barnet C, Samson G, Guerin P, Vahanian A, Mewton N; MITRA-FR Investigators. Percutaneous repair or medical treatment for secondary mitral regurgitation. *N Engl J Med* 2018;**379**:2297–2306.
- Chaput M, Handschumacher MD, Tournoux F, Hua L, Guerrero JL, Vlahakes GJ, Levine RA. Mitral leaflet adaptation to ventricular remodeling: occurrence and adequacy in patients with functional mitral regurgitation. *Circulation* 2008;**118**:845–852.
- Mullens W, Martens P. Sacubitril/valsartan to reduce secondary mitral regurgitation. *Circulation* 2019;**139**:1366–1370.
- Lancellotti P, Fattouch K, La Canna G. Therapeutic decision-making for patients with fluctuating mitral regurgitation. *Nat Rev Cardiol* 2015;**12**:212–219.
- Agricola E, Oppizzi M, Maisano F, De Bonis M, Schinkel AF, Torracca L, Margonato A, Melisurgo G, Alfieri O. Echocardiographic classification of chronic ischemic mitral regurgitation caused by restricted motion according to tethering pattern. *Eur J Echocardiogr* 2004;**5**:326–334.
- Bertrand PB, Schwammenthal E, Levine RA, Vandervoort PM. Exercise dynamics in secondary mitral regurgitation: pathophysiology and therapeutic implications. *Circulation* 2017;**135**:297–314.
- Bartko PE, Pavo N, Pérez-Serradilla A, Arfsten H, Neuhold S, Wurm R, Lang IM, Strunk G, Dal-Bianco JP, Levine RA, Hülsmann M, Goliasch G. Evolution of secondary mitral regurgitation. *Eur Heart J Cardiovasc Imaging* 2018;**19**:622–629.
- Grayburn PA, Sannino A, Packer M. Proportionate and disproportionate functional mitral regurgitation: a new conceptual framework that reconciles the results of the MITRA-FR and COAPT Trials. *JACC Cardiovasc Imaging* 2019;**12**:353–362.
- Liang JJ, Silvestry FE. Mechanistic insights into mitral regurgitation due to atrial fibrillation: "atrial functional mitral regurgitation". *Trends Cardiovasc Med* 2016;**26**:681–689.
- Deferm S, Bertrand PB, Verbrugge FH, Verhaert D, Rega F, Thomas JD, Vandervoort PM. Atrial functional mitral regurgitation: JACC review topic of the week. *J Am Coll Cardiol* 2019;**73**:2465–2476.
- Grigioni F, Enriquez-Sarano M, Zehr KJ, Bailey KR, Tajik AJ. Ischemic mitral regurgitation: long-term outcome and prognostic implications with quantitative Doppler assessment. *Circulation* 2001;**103**:1759–1764.
- Agricola E, Ielasi A, Oppizzi M, Faggiano P, Ferri L, Calabrese A, Vizzardi E, Alfieri O, Margonato A. Long-term prognosis of medically treated patients with functional mitral regurgitation and left ventricular dysfunction. *Eur J Heart Fail* 2009;**11**:581–587.
- Lancellotti P, Tribouilloy C, Hagendorff A, Popescu BA, Edvardsen T, Pierard LA, Badano L, Zamorano JL, Scientific Document Committee of the European Association of Cardiovascular Imaging. Recommendations for the echocardiographic assessment of native valvular regurgitation: an executive summary from the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging* 2013;**14**:611–644.
- Lancellotti P, Troisfontaines P, Toussaint AC, Pierard LA. Prognostic importance of exercise-induced changes in mitral regurgitation in patients with chronic ischemic left ventricular dysfunction. *Circulation* 2003;**108**:1713–1717.
- Piérad LA, Lancellotti P. The role of ischemic mitral regurgitation in the pathogenesis of acute pulmonary edema. *N Engl J Med* 2004;**351**:1627–1634.
- Delgado V, Tops LF, Schuijff JD, de Roos A, Brugada J, Schalij MJ, Thomas JD, Bax JJ. Assessment of mitral valve anatomy and geometry with multislice computed tomography. *JACC Cardiovasc Imaging* 2009;**2**:556–565.
- Therault-Lauzier P, Dorfmeister M, Mylotte D, Andalib A, Spaziano M, Blanke P, Martucci G, Lange R, Leipsic J, Bilodeau L, Piazza N. Quantitative multi-slice computed tomography assessment of the mitral valvular complex for transcatheter mitral valve interventions part 2: geometrical measurements in patients with functional mitral regurgitation. *EuroIntervention* 2016;**12**:e1021–e1030.
- Thavendiranathan P, Phelan D, Thomas JD, Flamm SD, Marwick TH. Quantitative assessment of mitral regurgitation: validation of new methods. *J Am Coll Cardiol* 2012;**60**:1470–1483.
- Zamorano JL, Fernández-Golfín C, González-Gómez A. Quantification of mitral regurgitation by echocardiography. *Heart* 2015;**101**:146–154.
- Bartko PE, Arfsten H, Heitzinger G, Pavo N, Toma A, Strunk G, Hengstenberg C, Hulsmann M, Goliasch G. A unifying concept for the quantitative assessment of secondary mitral regurgitation. *J Am Coll Cardiol* 2019;**73**:2506–2517.
- Lancellotti P, Zamorano JL, Vannan MA. Imaging challenges in secondary mitral regurgitation: unsolved issues and perspectives. *Circ Cardiovasc Imaging* 2014;**7**:735–746.
- Otto CM, Nishimura RA, Bonow RO, Carabello BA, Erwin JP 3rd, Gentile F, Jneid H, Krieger EV, Mack M, McLeod C, O'Gara PT, Rigolin VH, Sundt TM 3rd, Thompson A, Toly C. 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**:e35–e71.
- Zoghbi WA, Adams D, Bonow RO, Enriquez-Sarano M, Foster E, Grayburn PA, Hahn RT, Han Y, Hung J, Lang RM, Little SH, Shah DJ, Shernan S, Thavendiranathan P, Thomas JD, Weissman NJ. Recommendations for noninvasive evaluation of native valvular regurgitation: a report from the American Society of Echocardiography developed in collaboration with the Society for Cardiovascular Magnetic Resonance. *J Am Soc Echocardiogr* 2017;**30**:303–371.
- Rossi A, Dini FL, Faggiano P, Agricola E, Ciccoira M, Frattini S, Simioniuc A, Gullace M, Ghio S, Enriquez-Sarano M, Temporelli PL. Independent prognostic value of functional mitral regurgitation in patients with heart failure. A quantitative analysis of 1256 patients with ischaemic and non-ischaemic dilated cardiomyopathy. *Heart* 2011;**97**:1675–1680.
- Little SH, Pirat B, Kumar R, Igo SR, McCulloch M, Hartley CJ, Xu J, Zoghbi WA. Three-dimensional color Doppler echocardiography for direct measurement of vena contracta area in mitral regurgitation: in vitro validation and clinical experience. *JACC Cardiovasc Imaging* 2008;**1**:695–704.

38. Zeng X, Levine RA, Hua L, Morris EL, Kang Y, Flaherty M, Morgan NV, Hung J. Diagnostic value of vena contracta area in the quantification of mitral regurgitation severity by color Doppler 3D echocardiography. *Circ Cardiovasc Imaging* 2011;**4**:506–513.
39. Seferovic PM, Ponikowski P, Anker SD, Bauersachs J, Chioncel O, Cleland JGF, Boer RA, Drexler H, Ben Gal T, Hill L, Jaarsma T, Jankowska EA, Anker MS, Lainscak M, Lewis BS, McDonagh T, Metra M, Milicic D, Mullens W, Piepoli MF, Rosano G, Ruschitzka F, Volterrani M, Voors AA, Filippatos G, Coats AJS. Clinical practice update on heart failure 2019: pharmacotherapy, procedures, devices and patient management. An expert consensus meeting report of the Heart Failure Association of the European Society of Cardiology. *Eur J Heart Fail* 2019;**21**:1169–1186.
40. Crespo-Leiro MG, Metra M, Lund LH, Milicic D, Costanzo MR, Filippatos G, Gustafsson F, Tsui S, Barge-Caballero E, De Jonge N, Frigerio M, Hamdan R, Hasin T, Hulsmann M, Nalabangil T, Potena M, Milicic D, Mullens W, Gkouziota A, Ruyter A, Ristic AD, Straburzynska-Migaj E, McDonagh T, Seferovic P, Ruschitzka F. Advanced heart failure: a position statement of the Heart Failure Association of the European Society of Cardiology. *Eur J Heart Fail* 2018;**20**:1505–1535.
41. Neumann F-J, Sousa-Uva M, Ahlsson A, Alfonso F, Banning AP, Benedetto U, Byrne RA, Collet J-P, Falk V, Head SJ, Juni P, Kastrati A, Koller A, Kristensen SD, Niebauer J, Richter DJ, Seferovic PM, Sibbing D, Stefanini GG, Windecker S, Yadav R, Zembala MO; ESC Scientific Document Group. 2018 ESC/EACTS Guidelines on myocardial revascularization. *Eur Heart J* 2019;**40**:87–165.
42. Doughty RN, Whalley GA, Walsh HA, Gamble GD, López-Sendón J, Sharpe N, CAPRICORN Echo Substudy Investigators. Effects of carvedilol on left ventricular remodelling after acute myocardial infarction: the CAPRICORN Echo Substudy. *Circulation* 2004;**109**:201–206.
43. Solomon SD, Skali H, Anavekar NS, Bourgoun M, Barvik S, Ghali JK, Warnica JW, Khrakovskaya M, Arnold JM, Schwartz Y, Velazquez EJ, Califf RM, McMurray JJ, Pfeffer MA. Changes in ventricular size and function in patients treated with valsartan, captopril, or both after myocardial infarction. *Circulation* 2005;**111**:3411–3419.
44. Lowes BD, Gill EA, Abraham WT, Larrain JR, Robertson AD, Bristow MR, Gilbert EM. Effects of carvedilol on left ventricular mass, chamber geometry, and mitral regurgitation in chronic heart failure. *Am J Cardiol* 1999;**83**:1201–1205.
45. Waagstein F, Stromblad O, Andersson B, Bohm M, Darius M, Delius W, Goss F, Osterziel KJ, Sigmund M, Trenkwalder SP, Wahlgvist I. Increased exercise ejection fraction and reversed remodelling after long-term treatment with metoprolol in congestive heart failure: a randomized, stratified, double-blind, placebo-controlled trial in mild to moderate heart failure due to ischemic or idiopathic dilated cardiomyopathy. *Eur J Heart Fail* 2003;**5**:679–691.
46. Kang DH, Park SJ, Shin SH, Hong GR, Lee S, Kim MS, Yun SC, Song JM, Park SW, Kim JJ. Angiotensin receptor neprilysin inhibitor for functional mitral regurgitation. *Circulation* 2019;**139**:1354–1365.
47. Palardy M, Stevenson LW, Tasissa G, Hamilton MA, Bourge RC, Disalvo TG, Elkayam U, Hill JA, Reimold SC; ESCAPE Investigators. Reduction in mitral regurgitation during therapy guided by measured filling pressures in the ESCAPE trial. *Circ Heart Fail* 2009;**2**:181–188.
48. Gertz ZM, Raina A, Saghy L, Zado ES, Callans DJ, Marchlinski FE, Keane MG, Silvestry FE. Evidence of atrial functional mitral regurgitation due to atrial fibrillation: reversal with arrhythmia control. *J Am Coll Cardiol* 2011;**58**:1474–1481.
49. Erlebacher JA, Barbarash S. Intraventricular conduction delay and functional mitral regurgitation. *Am J Cardiol* 2001;**88**:A7, 83–86.
50. Cleland JG, Daubert JC, Erdmann E, Freemantle N, Gras D, Kappenberger L, Tavazzi L; Cardiac Resynchronization-Heart Failure (CARE-HF) Study Investigators. The effect of cardiac resynchronization on morbidity and mortality in heart failure. *N Engl J Med* 2005;**352**:1539–1549.
51. Ypenburg C, Lancellotti P, Tops LF, Bleeker GB, Holman ER, Pierard LA, Schalij MJ, Bax JJ. Acute effects of initiation and withdrawal of cardiac resynchronization therapy on papillary muscle dyssynchrony and mitral regurgitation. *J Am Coll Cardiol* 2007;**50**:2071–2077.
52. Ghio S, Freemantle N, Scelsi L, Serio A, Magrini G, Pasotti M, Shankar A, Cleland JG, Tavazzi L. Long-term left ventricular reverse remodelling with cardiac resynchronization therapy: results from the CARE-HF trial. *Eur J Heart Fail* 2009;**11**:480–488.
53. Di Biase L, Auricchio A, Mohanty P, Bai R, Kautzner J, Pieragnoli P, Regoli F, Sorgente A, Spinucci G, Ricciardi G, Michelucci A, Perrotta L, Faletta F, Mlcochova H, Sedlacek K, Canby R, Sanchez JE, Horton R, Burkhardt JD, Moccetti T, Padeletti L, Natale A. Impact of cardiac resynchronization therapy on the severity of mitral regurgitation. *Europace* 2011;**13**:829–838.
54. van Bommel RJ, Marsan NA, Delgado V, Borleffs CJ, van Rijnsvoever EP, Schalij MJ, Bax JJ. Cardiac resynchronization therapy as a therapeutic option in patients with moderate-severe functional mitral regurgitation and high operative risk. *Circulation* 2011;**124**:912–919.
55. Cleland J, Freemantle N, Ghio S, Fruhwald F, Shankar A, Marijanowski M, Verboven Y, Tavazzi L. Predicting the long-term effects of cardiac resynchronization therapy on mortality from baseline variables and the early response: a report from the CARE-HF (Cardiac Resynchronization in Heart Failure) Trial. *J Am Coll Cardiol* 2008;**52**:438–445.
56. Velazquez EJ, Lee KL, Deja MA, Jain A, Sopko G, Marchenko A, Ali IS, Pohost G, Gradinac S, Abraham WT, Yip M, Prabhakaran D, Szved H, Ferrazzi P, Petrie MC, O'Connor CM, Panchavinnin P, She L, Bonow RO, Rankin GR, Jones RH, Rouleau JL, STICH Investigators. Coronary-artery bypass surgery in patients with left ventricular dysfunction. *N Engl J Med* 2011;**364**:1607–1616.
57. Trichon BH, Glower DD, Shaw LK, Cabell CH, Anstrom KJ, Felker GM, O'Connor CM. Survival after coronary revascularization, with and without mitral valve surgery, in patients with ischemic mitral regurgitation. *Circulation* 2003;**108**:1103–1110.
58. Castleberry AW, Williams JB, Daneshmand MA, Honeycutt E, Shaw LK, Samad Z, Lopes RD, Alexander JH, Mathew JP, Velazquez EJ, Milano CA, Smith PK. Surgical revascularization is associated with maximal survival in patients with ischemic mitral regurgitation: a 20-year experience. *Circulation* 2014;**129**:2547–2556.
59. Samad Z, Shaw LK, Phelan M, Erbsoll M, Risum N, Al-Khalidi HR, Glower DD, Milano CA, Alexander JH, O'Connor CM, Wang A, Velazquez EJ. Management and outcomes in patients with moderate or severe functional mitral regurgitation and severe left ventricular dysfunction. *Eur Heart J* 2015;**36**:2733–2741.
60. Aklog L, Filsoufi F, Flores KQ, Chen RH, Cohn LH, Nathan NS, Byrne JG, Adams DH. Does coronary artery bypass grafting alone correct moderate ischemic mitral regurgitation? *Circulation* 2001;**104**:168–175.
61. Campwala SZ, Bansal RC, Wang N, Razzouk A, Pai RG. Factors affecting regression of mitral regurgitation following isolated coronary artery bypass surgery. *Eur J Cardiothorac Surg* 2005;**28**:783–787.
62. Yousefzai R, Bajaj N, Krishnaswamy A, Goel SS, Agarwal S, Aksoy O, Aggarwal B, Duarte VE, Anabtawi A, Parashar A, Sodhi N, Thomas J, Griffin BP, Tuzcu EM, Kapadia SR. Outcomes of patients with ischemic mitral regurgitation undergoing percutaneous coronary intervention. *Am J Cardiol* 2014;**114**:1011–1017.
63. Goyal P, Kim J, Feher A, Ma CL, Gurevich S, Veal DR, Szulc M, Wong FJ, Ratcliffe MB, Levine RA, Devereux RB, Weinsaft JW. Myocardial perfusion pattern for stratification of ischemic mitral regurgitation response to percutaneous coronary intervention. *Coron Artery Dis* 2015;**26**:642–650.
64. Bax JJ, Braun J, Somer ST, Klautz R, Holman ER, Versteegh MI, Boersma E, Schalij MJ, van der Wall EE, Dion RA. Restrictive annuloplasty and coronary revascularization in ischemic mitral regurgitation results in reverse left ventricular remodeling. *Circulation* 2004;**110**:1103–1110.
65. Petrus AHJ, Dekkers OM, Tops LF, Timmer E, Klautz RJM, Braun J. Impact of re-current mitral regurgitation after mitral valve repair for functional mitral regurgitation: long-term analysis of competing outcomes. *Eur Heart J* 2019;**40**:2206–2214.
66. Goldstein D, Moskowitz AJ, Gelijns AC, Ailawadi G, Parides MK, Perrault LP, Hung JW, Voisine P, Dagenais F, Gillinov AM, Thourani V, Argenziano M, Gammie JS, Mack M, Demers P, Atluri P, Rose EA, O'Sullivan K, Williams DL, Bagiella E, Michler RE, Weisel RD, Miller MA, Geller NL, Taddei-Peters WC, Smith PK, Moquete E, Overbey JR, Kron IL, O'Gara PT, Acker MA; CTSN. Two-year outcomes of surgical treatment of severe ischemic mitral regurgitation. *N Engl J Med* 2016;**374**:344–353.
67. Harmel EK, Reichenspurner H, Girdauskas E. Subannular reconstruction in secondary mitral regurgitation: a meta-analysis. *Heart* 2018;**104**:1783–1790.
68. Mirabel M, lung B, Baron G, Messika-Zeitoun D, Detaint D, Vanoverschelde JL, Butchart EG, Ravaud P, Vahanian A. What are the characteristics of patients with severe, symptomatic, mitral regurgitation who are denied surgery? *Eur Heart J* 2007;**28**:1358–1365.
69. Adamo M, Godino C, Giannini C, Scotti A, Liga R, Curello S, Fiorina C, Chiari E, Chizzola G, Abbenante A, Visco E, Branca L, Fiorelli F, Agricola E, Stella S, Lombardi C, Colombo A, Petronio AS, Metra M, Etti F. Left ventricular reverse remodelling predicts long-term outcomes in patients with functional mitral regurgitation undergoing MitraClip therapy: results from a multicentre registry. *Eur J Heart Fail* 2018;**21**:196–204.
70. Geis NA, Puls M, Lubos E, Zuern CS, Franke J, Schueler R, von Bardeleben RS, Boekstegers P, Ouarrak T, Zahn R, Ince H, Senges J, Katus HA, Bekeredjian R. Safety and efficacy of MitraClip™ therapy in patients with severely impaired left ventricular ejection fraction: results from the German transcatheter mitral valve interventions (TRAMI) registry. *Eur J Heart Fail* 2018;**20**:598–608.
71. Neuss M, Schau T, Schoepp M, Seifert M, Holschermann F, Meyhofer J, Butter C. Patient selection criteria and midterm clinical outcome for MitraClip therapy in patients with severe mitral regurgitation and severe congestive heart failure. *Eur J Heart Fail* 2013;**15**:786–795.
72. Nickenig G, Estevez-Loureiro R, Franzen O, Tamburino C, Vanderheyden M, Lüscher TF, Moat N, Price S, Dall'Ara G, Winter R, Corti R, Grasso C, Snow TM, Jeger R, Blankenberg S, Settergren M, Tiroch K, Balzer J, Petronio AS,



- Büttner H-J, Etori F, Sievert H, Fiorino MG, Claeys M, Ussia GP, Baumgartner H, Scandura S, Alamgir F, Keshavarzi F, Colombo A, Maisano F, Ebelt H, Aruta P, Lubos E, Plicht B, Schueler R, Pighi M, Di Mario C, Transcatheter Valve Treatment Sentinel Registry Investigators of the EURObservational Research Programme of the European Society of Cardiology. Percutaneous mitral valve edge-to-edge repair: in-hospital results and 1-year follow-up of 628 patients of the 2011-2012 Pilot European Sentinel Registry. *J Am Coll Cardiol* 2014;**64**: 875–884.
73. Swaans MJ, Bakker AL, Alipour A, Post MC, Kelder JC, de Kroon TL, Eefting FD, Rensing BJ, Van der Heyden JA. Survival of transcatheter mitral valve repair compared with surgical and conservative treatment in high-surgical-risk patients. *JACC Cardiovasc Interv* 2014;**7**:875–881.
74. Velazquez EJ, Samad Z, Al-Khalidi HR, Sangli C, Grayburn PA, Massaro JM, Stevens SR, Feldman TE, Krucoff MW. The MitraClip and survival in patients with mitral regurgitation at high risk for surgery: a propensity-matched comparison. *Am Heart J* 2015;**170**:1050–1059.e3.
75. Giannini C, Fiorelli F, De Carlo M, Guarracino F, Faggioni M, Giordano P, Spontoni P, Pieroni A, Petronio AS. Comparison of percutaneous mitral valve repair versus conservative treatment in severe functional mitral regurgitation. *Am J Cardiol* 2016;**117**:271–277.
76. Keßler M, Seeger J, Muehle R, Wöhrle J, Rottbauer W, Markovic S. Predictors of rehospitalization after percutaneous edge-to-edge mitral valve repair by MitraClip implantation. *Eur J Heart Fail* 2019;**21**:182–192.
77. Puls M, Lubos E, Boekstegers P, von Bardeleben RS, Ouarrak T, Butter C, Zuern CS, Bekeredjian R, Sievert H, Nickenig G, Eggebrecht H, Senges J, Schillinger W. One-year outcomes and predictors of mortality after MitraClip therapy in contemporary clinical practice: results from the German transcatheter mitral valve interventions registry. *Eur Heart J* 2016;**37**:703–712.
78. Praz F, Grasso C, Taramasso M, Baumbach A, Piazza N, Tamburino C, Windecker S, Maisano F, Prendergast B. Mitral regurgitation in heart failure: time for a rethink. *Eur Heart J* 2019;**40**:2189–2193.
79. lung B, Armoiry X, Vahanian A, Boutitie F, Mewton N, Trochu J-N, Lefèvre T, Messika-Zeitoun D, Guerin P, Cormier B, Brochet E, Thibault H, Himbert D, Thivoleat S, Leurent G, Bonnet G, Donal E, Piriou N, Piot C, Habib G, Rouleau F, Carrié D, Nejari M, Ohlmann P, Saint Etienne C, Leroux L, Gilard M, Samson G, Rioufol G, Maucort-Boulch D, Obadia JF, Obadia J-F; MITRA-FR Investigators. Percutaneous repair or medical treatment for secondary mitral regurgitation: outcomes at 2 years. *Eur J Heart Fail* 2019;**21**:1619–1627.
80. Asch FM, Grayburn PA, Siegel RJ, Kar S, Lim DS, Zaroff JG, Mishell JM, Whisenant B, Mack MJ, Lindenfeld J, Abraham WT, Stone GW, Weissman NJ, COAPT Investigators. Echocardiographic outcomes after transcatheter leaflet approximation in patients with secondary mitral regurgitation: the COAPT trial. *J Am Coll Cardiol* 2019;**74**:2969–2979.
81. Mendez OA. COAPT: Three-Year Outcomes from a Randomized Trial of Transcatheter Mitral Valve Leaflet Approximation in Patients with Heart Failure and Secondary Mitral Regurgitation. Oral presentation at Transcatheter Cardiovascular Therapeutics (TCT) congress 2019; San Francisco. 2019. <https://www.tctmd.com/slide/coapt-three-year-outcomes-randomized-trial-transcatheter-mitral-valve-leaflet-approximation> (14 February 2021).
82. Baron SJ, Wang K, Arnold SV, Magnuson EA, Whisenant B, Brieke A, Rinaldi M, Asgar AW, Lindenfeld J, Abraham WT, Mack MJ, Stone GW, Cohen DJ, COAPT Investigators. Cost-effectiveness of transcatheter mitral valve repair versus medical therapy in patients with heart failure and secondary mitral regurgitation: results from the COAPT trial. *Circulation* 2019;**140**:1881–1891.
83. Arnold SV, Chinnakondepalli KM, Spertus JA, Magnuson EA, Baron SJ, Kar S, Lim DS, Mishell JM, Abraham WT, Lindenfeld JA, Mack MJ, Stone GW, Cohen DJ, COAPT Investigators. Health status after transcatheter mitral-valve repair in heart failure and secondary mitral regurgitation: COAPT trial. *J Am Coll Cardiol* 2019;**73**:2123–2132.
84. Messika-Zeitoun D, lung B, Armoiry X. Impact of mitral regurgitation severity and left ventricular remodeling on outcome after MitraClip implantation: results from the MITRA-FR trial. *J Am Coll Cardiol Img* 2020; doi:10.1016/j.jcmg.2020.07.021.
85. Giustino G, Lindenfeld J, Abraham WT, Kar S, Lim DS, Grayburn PA, Kapadia SR, Cohen DJ, Kotinkaduwa LN, Weissman NJ, Mack MJ, Stone GW. NYHA functional classification and outcomes after transcatheter mitral valve repair in heart failure: the COAPT trial. *JACC Cardiovasc Interv* 2020;**13**:2317–2328.
86. Malik UI, Ambrosy AP, Ku IA, Mishell JM, Kar S, Lim DS, Whisenant BK, Cohen DJ, Arnold SV, Kotinkaduwa LN, Lindenfeld J, Abraham WT, Mack MJ, Stone GW. Baseline functional capacity and transcatheter mitral valve repair in heart failure with secondary mitral regurgitation. *JACC Cardiovasc Interv* 2020;**13**:2331–2341.
87. Kosmidou I, Lindenfeld J, Abraham WT, Kar S, Lim DS, Mishell JM, Whisenant BK, Kipperman RM, Boudoulas KD, Redfors B, Shahim B, Zhang Z, Mack MJ, Stone GW. Transcatheter mitral valve repair in patients with and without cardiac resynchronization therapy: the COAPT trial. *Circ Heart Fail* 2020;**13**:e007293.
88. Witte KK, Lipiecki J, Siminiak T, Meredith IT, Malkin CJ, Goldberg SL, Stark MA, von Bardeleben RS, Cremer PC, Jaber WA, Celermajer DS, Kaye DM, Sievert H. The REDUCE FMR trial: a randomized sham-controlled study of percutaneous mitral annuloplasty in functional mitral regurgitation. *J Am Coll Cardiol Heart Fail* 2019;**7**:945–955.
89. Messika-Zeitoun D, Nickenig G, Latib A, Kuck KH, Baldus S, Schueler R, La Canna G, Agricola E, Kreidel F, Huntgeburth M, Zuber M, Verta P, Grayburn P, Vahanian A, Maisano F. Transcatheter mitral valve repair for functional mitral regurgitation using the Cardioband system: 1 year outcomes. *Eur Heart J* 2019;**40**:466–472.
90. Praz F, Spargias K, Chrissoheris M, Bullesfeld L, Nickenig G, Deuschl F, Schueler R, Fam NP, Moss R, Makar M, Boone R, Edwards J, Moschovitis A, Kar S, Webb J, Schafer U, Feldman T, Windecker S. Compassionate use of the PASCAL transcatheter mitral valve repair system for patients with severe mitral regurgitation: a multicentre, prospective, observational, first-in-man study. *Lancet* 2017;**390**:773–780.
91. Lim DS, Kar S, Spargias K, Kipperman RM, O'Neill WW, Ng MKC, Fam NP, Walters DL, Webb JG, Smith RL, Rinaldi MJ, Latib A, Cohen GN, Schäfer U, Marcoff L, Vandragi P, Verta P, Feldman TE. Transcatheter valve repair for patients with mitral regurgitation: 30-day results of the CLASP study. *JACC Cardiovasc Interv* 2019;**12**:1369–1378.
92. lung B, Delgado V, Lazure P, Murray S, Sirnes PA, Rosenhek R, Price S, Metra M, Carrera C, De Bonis M, Haude M, Hindricks G, Bax J, Vahanian A. Educational needs and application of guidelines in the management of patients with mitral regurgitation. A European mixed-methods study. *Eur Heart J* 2018;**39**:1295–1303.
93. Lund LH. Optimizing outcomes after heart transplantation. *Eur J Heart Fail* 2018;**20**:395–397.
94. Thorvaldsen T, Lund LH. Focusing on referral rather than selection for advanced heart failure therapies. *Card Fail Rev* 2019;**5**:24–26.
95. Bonow RO, O'Gara PT, Adams DH, Badhwar V, Bavaria JE, Elmariah S, Hung JW, Lindenfeld J, Ann, Morris AA, Satpathy R, Whisenant B, Woo YJ. 2020 Focused update of the 2017 ACC Expert Consensus Decision Pathway on the management of mitral regurgitation: a report of the American College of Cardiology Solution Set Oversight Committee. *J Am Coll Cardiol* 2020;**75**:2236–2270.

## Corrigendum

doi:10.1093/eurheartj/ehaa998

Online publish-ahead-of-print 9 December 2020

**Corrigendum to:** Gone with wind: a novel biodegradable occluder for percutaneous closure of patent foramen ovale.

DOI: 10.1093/eurheartj/ehaa807.

In the originally published version of this manuscript, the word 'arterial septum' should be corrected as 'atrial septum'. This has now been corrected online.