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Review

Multimodality Cardiac Imaging Evaluation and Guidance of Management for Aortic Regurgitation

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Abstract

Aortic regurgitation (AR) is a valvular heart disease characterized by the pathological backflow of blood from the aorta into the left ventricle during diastole, causing left ventricular pressure and volume overload. This results in dilation and enlargement of the left ventricle, causing left ventricular hypertrophy and, ultimately, left ventricular dysfunction. AR has a wide range of causes, which include congenital, acquired, and genetic diseases. Therefore, AR may present as an acute condition causing hemodynamic compromise or as a chronic condition with a long asymptomatic phase, which could progress to heart failure (HF). The clinical profile and the disease trajectory depend on the age, sex, and the type of underlying AR pathology. Noninvasive cardiac multimodality imaging (cMMI) has been integral in the serial monitoring and management of AR. Meanwhile, transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) are mainly utilized as the first-line diagnosis and monitoring options for AR. Furthermore, cardiac magnetic resonance imaging (CMR) is useful in assessing regurgitant volume and the degree of myocardial remodeling. Cardiac computed tomography (CT) is another second-line imaging modality used to evaluate anatomy, particularly for surgical planning. These modalities allow a systematic assessment of AR disease severity and therapeutic decision-making. Surgical aortic valve replacement (SAVR) is the recommended modality for treating severe symptomatic AR. Meanwhile, transcatheter aortic valve replacement (TAVR) may be a potential interventional option for patients at elevated surgical risk; however, the evidence remains limited to patients with mixed aortic valvular disease. Therefore, new research is currently being performed in artificial intelligence and four-dimensional imaging to optimize the diagnostic accuracy of imaging techniques and identify patients who would benefit from early intervention, thus improving outcomes. The primary objective of this review is to explore the different indications, advantages, and disadvantages of cMMI in the diagnosis, follow-up, and treatment of severe AR, highlighting how cMMI can be utilized in optimizing clinical decision-making and patient outcomes.

Keywords

aortic regurgitation; cardiac multimodality imaging; echocardiography; cardiac MRI; cardiac CT; left ventricular remodeling

Introduction

Aortic regurgitation (AR) is a pathological condition marked by progressive volume and pressure overload on the left ventricle (LV), ultimately resulting in adverse structural remodeling of the myocardium [1]. Numerous reports have emphasized the limitations of relying solely on single-modality linear LV dimension cutoffs and the variability in LV remodeling influenced by age and sex [2]. In addition to being a primary risk factor for developing AR, age significantly influences the LV response to hemodynamic overload. Hence, older individuals typically exhibit smaller LV dimensions than their younger counterparts, which may affect adaptive and pathological remodeling processes [3]. In the OxVALVE study, 1.6% of participants presented with moderate or severe AR [4]; in the Framingham Offspring study, AR prevalence also increased with age [5]. Similarly, sex appears to significantly influence LV dimensions and remodeling in states of chronic volume overload, whereby compared to men, women typically exhibit smaller LV volumes when indexed to body surface area (BSA) [6]. These prior findings further corroborate the critical importance of early diagnosis and timely management of AR, particularly considering the increasing aging population and sex-related differences in LV remodeling and timing of intervention. Moreover, these previous findings highlight major pitfalls and disparities in the current guidelines for managing chronic AR, which may lead to suboptimal timing of interventions and adversely affect clinical outcomes [7,8]. From this perspective, cardiac multimodality imaging (cMMI) serves as an integrative diagnostic tool to uncover the severity of AR and the coexistence of aortic abnormalities and gauge the optimal intervention timing. Echocardiography, the traditional modality used for AR diagnosis, severity quantification, and evaluation of LV

Table 1. Etiologies of aortic regurgitation.

Category	Causes
Congenital	• Bicuspid aortic valve • Outlet supra-cristal ventricular septal defect • Discrete subaortic stenosis
Degenerative	• Bicuspid aortic valve • Outlet supra-cristal ventricular septal defect • Discrete subaortic stenosis
Infectious	• Infective endocarditis • Rheumatic fever
Connective Tissue Disorders	• Marfan syndrome • Ehlers-Danlos syndrome • Osteogenesis imperfecta
Inflammatory/Autoimmune	• Ankylosing spondylitis • Reactive arthritis • Psoriatic arthritis • Rheumatoid arthritis • Systemic lupus erythematosus • Giant cell arteritis • Takayasu arteritis
Aortic Root Disorders	• Aortic dissection • Syphilitic aortitis • Cystic medial necrosis • Hypertension-induced aortic dilation
Traumatic	• Chest trauma • Aortic tear
Iatrogenic	• Complications from transcatheter aortic valve replacement (TAVR) • Left ventricular assist device (LVAD) implantation • Prosthetic valve malfunction

remodeling, can now be complemented by more advanced modalities such as cardiac computed tomography (CT) and cardiac magnetic resonance imaging (CMR), particularly in cases associated with ambiguous or inconsistent echocardiographic findings, or necessitating complex clinical decisions, including complex valvular and aortic surgery. Our review aims to explore the downstream multimodal imaging approach in patients with AR, highlighting the complementary role of each imaging modality in the diagnosis, longitudinal follow-up, and the decision to intervene.

Etiology and Classification

The aortic valve comprises three semilunar cusps attached to the aortic wall, constituting the sinuses of Valsalva. AR results from a wide range of congenital, acquired, and genetic abnormalities affecting the aortic valve leaflets, the aortic root, or both. These pathological changes lead to impaired leaflet coaptation and diastolic regurgitation of blood into the LV [9]. Table 1 summarizes the different causes of AR according to various etiologies [10].

Identifying the underlying mechanism through which AR occurs is essential for evaluating the feasibility of aortic valve repair. Indeed, functional classifications have been utilized for AR, such as adapting the Carpentier classification, which was initially developed for the mitral valve. These classifications assist in understanding the underlying mechanisms involved, guiding management, and predicting the likelihood of recurrence. The Carpentier classification system has been used to categorize dysfunction based mainly on aortic root and leaflet morphology (Table 2) [11].

When evaluating the aortic valve, it is important to consider mixed etiologies of regurgitation and stenosis, also known as mixed aortic valve disease (MAVD). A large retrospective study by Yang *et al*. [8] involving patients referred for surgical aortic valve replacement or repair identified leaflet prolapse combined with aortic root dilation as the most common mixed etiology. Similarly, a nationwide epidemiological study in Sweden by Andell *et al.* [12] found that 17.9% of patients with AR also had concomitant aortic stenosis (AS), making MVAD the most prevalent form of mixed valve disease. The coexistence of AS is clinically relevant, as studies indicate that patients with concomitant moderate AS and AR exhibit a prognosis comparable to or worse than that of patients with isolated AS or AR [13].

Table 2. Aortic regurgitation classifications.

Type	Description
Type I	Normal leaflet motion with pathology affecting the aortic root or valve
Type Ia	Sinotubular junction enlargement and ascending aorta dilation
Type Ib	Dilation of both sinuses of Valsalva and sinotubular junction
Type Ic	Dilation of the ventriculoaortic junction (annulus)
Type Id	Cusp perforation or fenestration without primary annular lesion
Type II	Excessive leaflet motion due to leaflet prolapse from redundant tissue or commissural disruption
Type III	Restricted leaflet motion, often due to congenital abnormalities, degenerative calcification, or leaflet thickening and fibrosis

Pathophysiology and Clinical Presentation

Significant differences exist in the natural history and clinical features of AR depending on aortic valve morphology. Patients with bicuspid valves usually develop AR at a younger age and often present a mixture of AR and AS [14]. In a large contemporary study involving 798 patients, Yang *et al.* [15] found that patients with bicuspid valves were, on average, two decades younger at presentation, underwent aortic valve surgery more frequently and experienced fewer complications than those with tricuspid valves. A strong link also existed between the baseline symptoms and chamber remodeling in the bicuspid valve group. Meanwhile, mortality risk in bicuspid valve patients was observed to increase after the ages of 50 to 55. However, after adjusting for age, this study noted that survival rates were comparable between the two groups [15].

Acute Aortic Regurgitation

AR triggers a cascade of adverse effects due to sudden volume overload in the LV that cannot immediately compensate through chamber dilation. This differs from chronic AR, where gradual remodeling allows patients to remain stable for years despite worsening regurgitation. In acute AR, the rapid increase in left ventricular end-diastolic pressure (LVEDP) can cause significant hemodynamic instability if not promptly managed. Hence, the sharp rise in LVEDP reduces the pressure gradient across the mitral valve, leading to reverberation, reverse doming of the anterior mitral valve leaflet and premature mitral valve closure. If LVEDP exceeds left atrial pressure, mitral regurgitation can occur during systole or diastole. Moreover, the timing of mitral valve closure can indicate the severity of acute AR and the degree of LVEDP elevation [16]. Elevated left atrial pressure and pulmonary congestion may also develop as upstream consequences. The deleterious effects of acute AR on the LV involve two primary mechanisms. First, when LVEDP approaches aortic diastolic pressure, subendocardial hypoperfusion may occur due to reduced LV myocardial perfusion pressure. Second, the volume overload and increased afterload increase systolic wall stress across the LV. Subsequently, the LV dilation and mitral valve annulus stretching may cause secondary mitral regurgitation.

Since the LV cannot immediately increase cardiac output, the heart rate rises to maintain adequate organ perfusion. Clinical signs and symptoms of acute AR include shortness of breath, tachycardia, chest discomfort, peripheral hypoperfusion, and pulmonary congestion. However, physical findings in acute AR are generally less pronounced than those seen in chronic severe AR.

Chronic Aortic Regurgitation

In chronic AR, LV remodeling in response to long-standing pressure and volume overload ensures forward flow. These structural adaptations aim to limit elevations in LVEDP at the expense of increasing LV chamber size (eccentric hypertrophy). Hence, LV cavity dilation is proportional to the severity and chronicity of the regurgitation [9].

When the preload reserve is exhausted, and hypertrophic adaptations can no longer compensate for the increased afterload, LV ejection fraction begins to decline, and heart failure (HF) symptoms develop [17,18]. Meanwhile, end-systolic wall stress in chronic severe AR can reach levels comparable to those observed for AS [19]. Conversely, in patients with MAVD, LV concentric hypertrophy and replacement fibrosis induced by AS reduces LV compliance, thus limiting the ability of the LV to offset the increased end-diastolic volume caused by AR [20]. Chronic AR is classified into four stages (A–D), ranging from patients at risk of developing AR (Stage A) to those with severe symptomatic AR (Stage D) [21]. The annual progression rate to symptoms or LV dysfunction in chronic AR is about 4–5%, while the average mortality rate remains below 0.2% per year [17,22]. Notably, most patients remain in the asymptomatic state for a long period; however, once HF ensues, survival significantly decreases in the absence of prompt corrective surgery [19].

The Role of Cardiac Multimodality Imaging

Echocardiographic Evaluation of Native AR

Transthoracic echocardiography (TTE) is the cornerstone option for the initial assessment of AR and determin-

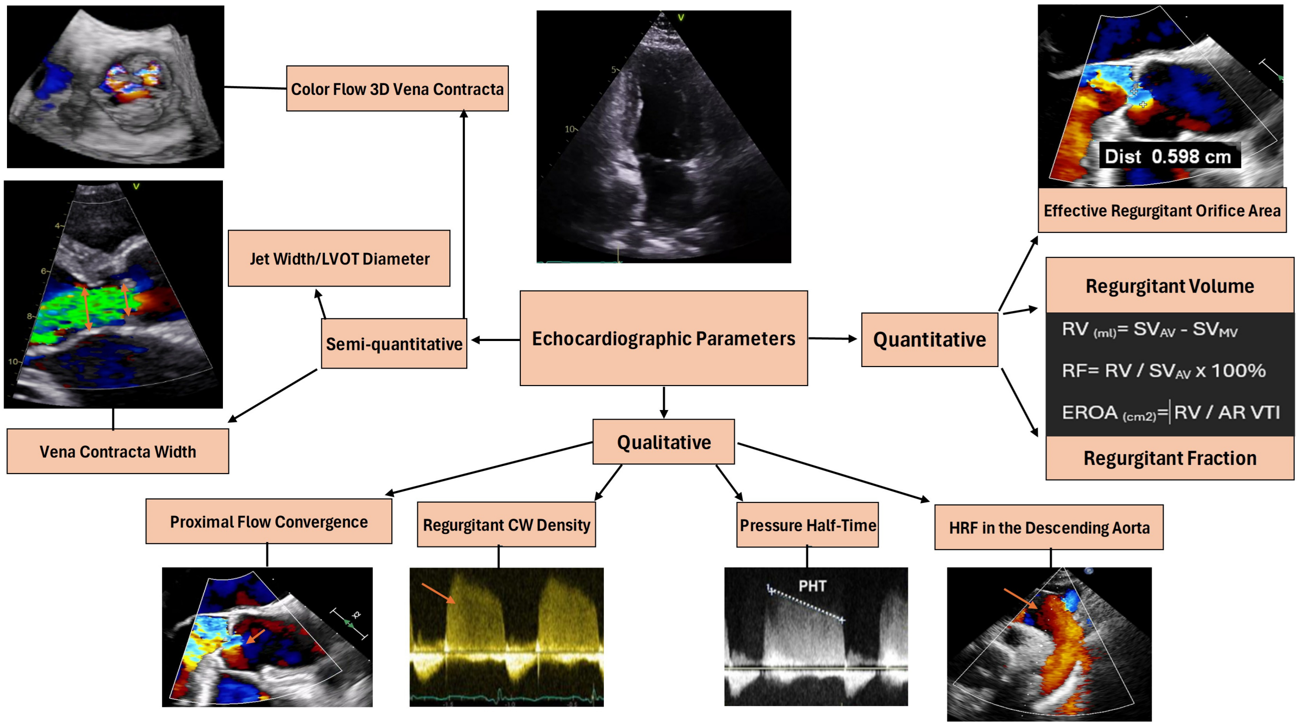

Fig. 1. An illustration of the key echocardiographic parameters utilized in the evaluation of native AR severity, encompassing qualitative, semi-quantitative, and quantitative assessment techniques. Notably, the effective regurgitant orifice area (EROA) formula for AR severity quantification requires adequate visualization of the proximal flow convergence on 2D color Doppler and measurement of the proximal isovelocity surface area (PISA). The radius (R = 0.598 cm) in the depicted image is in the upper right corner of the figure. Hence, the EROA is calculated using the formula: $EROA = 2\varpi R^2 \times$ aliasing velocity $\div$ peak AR jet velocity. Abbreviations: AR, aortic regurgitation; 2D, two-dimensional; PHT, pressure half time; LVOT, left ventricular outflow tract; 3D, three-dimensional; CW, continuous-wave Doppler; HRF, holo-diastolic flow reversal; RV, regurgitant volume; SV, stroke volume; AV, aortic valve; RF, regurgitant fraction; VTI, velocity–time integral.

ing the optimal timing for surgical intervention [9]. While mild tricuspid regurgitation (TR) and pulmonary regurgitation (PR) are commonly accepted as physiological findings, AR is always clinically important. The assessment begins with evaluating the morphology of the aortic valve and the aortic root to determine the etiology of the regurgitation, followed by an investigation of the LV size, geometry, and function [9]. When assessing the severity of AR using various Doppler methods, grading is performed using qualitative, semi-quantitative, and quantitative parameters (Fig. 1; Table 3) [9,21,23]. TTE is highly effective in quantifying AR severity using color Doppler, pressure half-time, and volumetric flow assessments.

The hemodynamic impact and cardiac adaptation differ between acute and chronic AR [9]. In severe acute AR, the LV is not dilated, and the sudden increase in LVEDP can cause premature mitral valve closure, best visualized using M-mode echocardiography. In contrast, chronic AR leads to progressive LV volume overload, resulting in gradual LV dilation and increasing the risk of progressively worsening HF. LV dilation or enlargement strongly suggests significant AR, provided the exclusion of other causes of LV volume overload and high-output states, such as athletic heart syndrome, hyperthyroidism, or anemia.

Stress echocardiography is an important diagnostic tool for both symptomatic and asymptomatic patients, allowing for evaluation of the functional capacity, detection of the underlying coronary artery disease, and assessment of the dynamic changes in LV size and function during exercise [9]. Meanwhile, since Transesophageal Echocardiography (TEE) provides superior spatial resolution compared to TTE, TEE offers enhanced visualization of valve morphology. Moreover, TEE facilitates a comprehensive assessment of both quantitative and qualitative parameters to confirm the severity of AR following suboptimal or inconclusive TTE findings. In patients with suspected aortic root involvement, such as in cases of aortic dissection or aneurysmal dilation, TEE is superior to TTE due to its ability to accurately visualize the aortic root and ascending aorta without interference from the chest wall or lung artifacts. Ultimately, TTE forms the pillar of the initial diagnosis and serial follow-up for AR; meanwhile, TEE serves as an adjunct in complex cases requiring enhanced structural detail, perioperative planning, or following insufficient,

Table 3. The grading of native and prosthetic aortic regurgitation across different echocardiographic parameters (structural, qualitative, semi-quantitative, quantitative) based on the 2017 Recommendations for Noninvasive Evaluation of Native Valvular Regurgitation and the 2024 Guidelines for the Evaluation of Prosthetic Valve Function with Cardiovascular Imaging from the American Society of Echocardiography.

	Regurgitation Severity					
	Mild		Moderate		Severe	
	Native AR	Prosthetic AR	Native AR	Prosthetic AR	Native AR	Prosthetic AR
Structural Parameters						
Anatomical Findings	Normal/Abnormal leaflets	Normal valve structure/motion	Normal/Abnormal leaflets	Normal valve structure/motion	Flail/wide coaptation defect	Abnormal valve structure/motion
LV Size	Normal	Normal	Normal or dilated	Normal or dilated	Dilated	Dilated
Qualitative Doppler Parameters						
Jet Width in LVOT, Color Flow	Small	Narrow (<25% of LVOT)	Intermediate	Intermediate (26–64% of LVOT)	Large in central jet/variable if eccentric	Large (>65% of LVOT)
Flow Convergence, Color Flow	None or very small	Not required/assessed	Intermediate	Not required/assessed	Large	Not required/assessed
Jet Density, CW	Incomplete or faint	Incomplete or faint	Dense	Dense	Dense	Dense
Jet Deceleration Rate, CW	Slow (>500 ms)	Slow (>500 ms)	Medium (200–500 ms)	Medium (200–500 ms)	Steep (<200 ms)	Steep (<200 ms)
Diastolic Flow Reversal in Descending Aorta, PW	Absent/brief early diastolic	Absent/brief early diastolic	Intermediate	Intermediate	Prominent/holodiastolic	Prominent/holodiastolic
Semiquantitative Parameters						
Vena Contracta Width (cm)	<0.3	<0.3	0.3–0.6	0.3–0.6	>0.6	>0.6
Vena Contracta Area (cm²)	Not required/assessed	<0.1	Not required/assessed	0.1–0.29	Not required/assessed	Not required/assessed
Jet Width/LVOT Width, Central Jets (%)	<0.25	<0.25	0.25–0.64	0.25–0.64	≥0.65	≥0.65
Jet CSA/LVOT CSA, Central Jets (%)	<5	Not required/assessed	5–69	Not required/assessed	≥60	Not required/assessed
Circumferential Extent of PVL (%)	Not required/assessed	<10	Not required/assessed	10–29	Not required/assessed	≥30
Quantitative Parameters						
Regurgitant Volume (mL)	≤30	≤30	30–59	30–59	≥60	≥60
Regurgitant Fraction (%)	<30	<30	30–49	30–50	≥50	≥50
EROA (cm²)	<10	Not required/assessed	10–29	Not required/assessed	≥30	Not required/assessed

Abbreviations: AR, aortic regurgitation; LV, left ventricle; LVOT, left ventricular outflow tract; CW, continuous-wave Doppler; PW, pulsed-wave Doppler; CSA, cross-sectional area; EROA, effective regurgitant orifice area.

inconsistent, or unreliable TTE imaging. Two-dimensional (2D) and three-dimensional (3D) TEE have demonstrated significant utility in evaluating prosthetic valves in the context of inflammatory or infectious endocarditis, detecting aortic root dilation and abscess formation, and assessing aortic injury or dissection. Moreover, TEE is a valuable tool in evaluating infective endocarditis, both native and prosthetic, mainly to delineate the size of vegetations and associated sequelae, such as aortic root abscess formation, pseudoaneurysm, leaflet perforation, fistulization or Gerbode defects, and valve dehiscence. Additionally, TEE plays a pivotal role in the presurgical evaluation of patients undergoing aortic root surgery, valve-sparing aortic procedures, or valve repair, as well as in planning transcatheter repair or replacement interventions [9]. Finally, speckle tracking echocardiography (STE) has garnered attention since its inception as a predictive tool for subclinical LV dysfunction, longitudinal monitoring, patient risk stratification, and post-operative risk prediction. Using global longitudinal strain (GLS), STE allows for subclinical LV dysfunction and impaired myocardial contractility to be identified in patients with severe AR and preserved LV ejection fraction. Indeed, LV GLS outperformed other traditional parameters in predicting the need for early aortic valve surgery [24]. Preoperative LV strain correlates with postoperative LV recovery, with an impaired strain ($<$15.8%) predicting persistent HF and LV systolic dysfunction after valvular surgery [25]. GLS values are initially elevated due to volume overload, normalizing during adaptive LV remodeling, then declining as HF develops (biphasic GLS pattern) [26].

Echocardiographic Evaluation of Prosthetic AR

The evaluation of prosthetic aortic valves using echocardiography and Doppler techniques should begin by determining the type and size of the implanted prosthetic valve, its position within the aortic root, the short-axis shape of the valve, the apposition of the valve stent to native aortic tissue, and the presence of aortic annular injury or ventricular septal defects. In addition to assessing the location and underlying mechanisms involved in AR, TTE facilitates the evaluation of prosthetic aortic regurgitation (PAR), including characterizing its underlying mechanism, identifying the jet origins, and detecting associated complications, such as endocarditis, abscess formation, intracardiac masses, and thrombi. However, due to acoustic reverberation and shadowing artifacts caused by the aortic prosthesis, which may hinder complete visualization of the posterior annulus and aortic root, TEE is often employed as a complementary modality. Nonetheless, TEE provides a more comprehensive intra- and paravalvular PAR assessment by integrating qualitative and semiquantitative parameters (Table 3) [27]. As with native AR, standard Doppler techniques are applied to evaluate PAR, including assessing the flow convergence, vena contracta (VC), and proximal jet extension into the left ventricular outflow tract (LVOT) and LV. However, these methods may be limited by reverberation and shadowing artifacts from the prosthetic valve, which can impair accurate visualization of the flow convergence zone, VC region, and jet width within the LVOT. Conversely, the prosthetic valve is generally unaffected by semiquantitative and quantitative spectral Doppler methods for grading AR severity (Table 3). In cases where the PAR severity and grading cannot be confidently determined, complementary imaging modalities such as CMR imaging or CT may be warranted. Each imaging modality offers distinct advantages and limitations, as summarized in Table 4.

Cardiac CT

Simply, cardiac CT does not typically represent a first-line imaging modality for assessing the severity of AR since it does not employ direct quantification of blood flow. However, in cases of moderate to severe AR, CT may reliably detect incomplete leaflet coaptation and offers the ability to quantify regurgitant orifice area (ROA) with a strong correlation to echocardiography (r = 0.86, $p < 0.001$), thus offering incremental data for intervention timing in uncertain cases. Additionally, since aortic diseases frequently coexist with aortic valve disorders, cardiac CT plays a crucial role in evaluating the aortic root and ascending aorta, which is fundamental for the stratification and surgical planning of patients with AR [9].

Owing to its high spatial resolution, CT is a commonly utilized adjunct imaging modality for assessing PAR suspected on echocardiography. Furthermore, CT enables detailed evaluation of valve morphology, structural abnormalities, regurgitant orifices, sewing ring complications, and paravalvular abnormalities. Cardiac CT is useful in setting multiple prosthetic heart valves that may cause significant artifacts and shadowing on TEE. CT prospective electrocardiographic (ECG) triggering is suitable for assessing aortic valve morphology, whereas retrospective ECG gating enables dynamic 3D evaluation and functional quantification. A non-contrast acquisition is valuable for identifying calcifications and postsurgical changes, while delayed-phase imaging aids in identifying abscess cavities with rim enhancement and thrombus. Moreover, CT angiography permits the identification of valve dehiscence and complications such as pseudoaneurysm formation [27]. Cardiac CT interrogates aortic annular dimensions, calcification patterns, and iliofemoral access routes for transcatheter interventions. However, while CT is limited in detecting mild AR with severe calcification or bicuspid valves, CT can be used to comprehensively validate anatomic profiling, rendering this modality indispensable for complex cases requiring multimodality decision-making.

Table 4. A comparative description of the different imaging modalities used to assess and manage AR and their associated indications, strengths, and limitations.

Imaging Modality	Indications	Strengths	Limitations
Transthoracic Echocardiography	1st-line for AR assessment	AoV morphology assessment	Low spatial resolution
	Monitoring AR progression	Initial and serial F/U on AR severity	Poor image quality with obesity and CLD
	Follow-up on LV size	Impact of AR on cardiac remodeling	Operator dependent
	Evaluation of aortopathy	Multiparametric assessment of AR severity	Interobserver and intraobserver variability
	Symptom evaluation	Comprehensive reproducible measurements	Flow dependence of Doppler measurements
	Pre-operative evaluation	Cost-effective	Artifact interference
	Follow-up after surgery	Non-invasive and readily available	Limited quantification of jet size/shape and RVol
Transoesophageal Echocardiography	Inconclusive initial TTE imaging	Superior image resolution	Limitations in complete visualization of aorta
	3D assessment of AoV morphology	Multiparametric assessment of AR severity	Prone to artifact and shadowing
	Suitability of transcatheter or surgical approaches	Detailed evaluation of IE	Patient discomfort and sedation requirement
	Evaluation of prosthetic AoV dysfunction and IE	Aortic abnormalities and presence of dissection	Contraindicated in esophageal disorders
	Intraoperative guidance for SAVR	Evaluation of subvalvular pathologies	Contraindicated in severe coagulopathy
	Guidance for transcatheter interventions	PVL severity and quantification	Flow dependence of Doppler measurements
Cardiac MRI	Inconclusive echocardiographic images	Excellent spatial resolution	Low temporal resolution
	BAV and incomplete aortic assessment by TEE	Free of ionizing radiation	Partial volume effects
	Discordant echocardiographic and Doppler findings	SSFP and endocardial contouring	Cardiac and respiratory motion artifacts
	Discordant symptoms and AR severity	Excellent signal to noise ratio	Requires breath-holding and patient cooperation
	BAV and incomplete visualization of aorta	High blood to myocardium contrast	Limitations in assessing complex flows
	Coexisting multiple valvular lesions	Direct SV, EF and RV measurements	Absence of accepted severity cutoffs
	Longitudinal patient F/U	Less interobserver and intrastudy variability	High cost and exam time
Cardiac CT	Assessment of AoV morphology	Superior spatial resolution	Low temporal resolution
	Planning for transcatheter interventions	AoV root and valve morphology	Lacks real-time evaluation
	Suitability for alternative access sites	Dynamic imaging using ECG-gating	Lacks hemodynamic assessment
	Aortic size and vascular calcifications	Prosthetic AoV interrogation	Radiation exposure
	Coronary artery evaluation	Complications of IE and AR	Contrast administration
	Evaluation of prosthetic AoV dysfunction	Pre-surgical planning	Subject to beam-hardening and streak artifact

Abbreviations: AR, aortic regurgitation; MRI, magnetic resonance imaging; CT, computed tomography; TTE, transthoracic echocardiogram; TEE, transesophageal echocardiogram; LV, left ventricle; SAVR, surgical aortic valve replacement; 3D, three-dimensional; AoV, aortic valve; BAV, bicuspid aortic valve; F/U, follow-up; PVL, paravalvular leak; RV, regurgitant volume; SV, stroke volume; EF, ejection fraction; SSFP, steady-state free precession; ARO, aortic regurgitation orifice; CW, continuous-wave Doppler; AS, aortic stenosis; Rvol, regurgitant volume; RF, regurgitant fraction; IE, infective endocarditis; ECG, electrocardiogram; CLD, chronic lung disease.

Cardiac Magnetic Resonance Imaging (MRI)

MRI Techniques for AR

CMR offers some advanced techniques for evaluating valvular regurgitation severity and hemodynamic aspects. Cine MRI provides high temporal and spatial resolution images of cardiac anatomy through balanced steady-state free precession (SSFP) sequences. In the context of AR, cine MRI allows for detailed visualization of valve morphology, leaflet motion, and the regurgitant jet. CMR is particularly useful in identifying the underlying etiology of AR and the presence/degree of LV remodeling [28,29].

Henceforth, four-dimensional (4D)-flow MRI captures 3D blood flow dynamics over time, offering comprehensive flow analysis within the heart and great arteries of heart. Additionally, this advanced modality provides direct visualization and accurate quantification of complex flow patterns, including eccentric or multiple regurgitant jets, which can be more challenging to assess. From this perspective, CMR represents a unique diagnostic tool, enabling a comprehensive assessment of the etiology, severity, and mechanism of AR and a detailed evaluation of myocardial remodeling and function. This integrative approach aids in accurately determining the optimal timing for intervention [30].

Quantification of Aortic Regurgitation and LV Remodeling Using MRI

CMR is pivotal in AR management because it quantifies regurgitation severity and risk stratification and guides intervention timing through advanced hemodynamic and anatomical assessments. Similar to echocardiography, CMR is utilized to precisely quantify AR through direct measurements of the same key parameters using phase-contrast imaging, which offers direct measurement of regurgitant volume (Rvol) and regurgitant fraction (RF) with high reproducibility and accuracy (Fig. 2). Rvol is the volume ejected back into the LV during diastole (LV stroke volume minus forward flow volume); RF is the regurgitant percentage of the LV stroke volume (Rvol/stroke volume*100); the effective regurgitant orifice area (EROA) is the area through which regurgitation occurs [31]. An RF >33% predicts progression to surgery within 3 years (85% sensitivity), while holo-diastolic flow reversal in the descending aorta independently correlates with adverse outcomes (HR 2.8 for heart failure/death) and is considered a trigger for early surgical referral [32].

An echocardiographic proximal isovelocity surface area (PISA) calculation of the ROA and CMR measurement of RF have both previously established prognostic values; however, CMR was reported to be superior to echocardiography, virtually outperforming the latter mainly in cases of diagnostic ambiguity or MAVD. Additionally, CMR was found to reclassify AR severity in 34% of echocardiographic classified "severe" cases and 45% of the "moderate–severe" cases, resolving diagnostic uncertainty.

CMR offers high spatial resolution and reproducibility, enabling precise volumetric assessments without relying on geometric assumptions and reducing angle dependence for flow measurements compared to TTE. A study by Harris *et al.* [33] compared the ability of TTE and CMR to predict clinical outcomes in patients with AR and mitral regurgitation (MR). Both imaging modalities were performed for 51 subjects on the same day; these individuals were followed for an average of 4.4 years. For AR, a CMR-derived regurgitant volume greater than 50 mL significantly predicted valve surgery more than TTE measurements. Meanwhile, both TTE and CMR performed similarly for MR; however, a TTE regurgitant volume greater than 30 mL was strongly associated with adverse outcomes. Overall, CMR demonstrated better prognostic value in AR, while both methods were comparable in MR. Another study by Myerson *et al.* [31] followed 113 patients with moderate to severe AR for an average of 2.6 years. The study found that 85% of patients with an RF greater than 33% progressed to surgery, primarily within three years, compared to only 8% of those with an RF lower than 33%. A CMR-derived left ventricular end-diastolic volume (LVEDV) greater than 246 mL provided significant prognostic value, especially when combined with right ventricular measurements. A study by Bolen *et al.* [34] at The Cleveland Clinic focused on high diastolic regurgitant flow (HDR) in the descending thoracic aorta, a marker for severe AR previously validated using TTE. CMR imaging effectively assessed HDR during routine clinical evaluations of aortic flow, showing high sensitivity (100%) and specificity (93%) for predicting severe AR. These findings collectively highlight the robust ability of CMR-derived metrics to identify patients at higher risk of adverse outcomes, thereby guiding the optimal timing for surgical intervention.

CMR appears to be similar to cardiac CT for 3D aortic root anatomy, annular sizing, and access route evaluations, especially in patients with renal insufficiency or contraindications for contrast administration, and can accurately detect those who are deemed critical for valve selection and combined coronary artery bypass planning [35].

Chronic volume overload in aortic regurgitation (AR) initiates compensatory mechanisms that lead to progressive left ventricular (LV) dilation and hypertrophy, ultimately resulting in myocardial fibrosis. Cardiovascular magnetic resonance (CMR) plays a pivotal role in evaluating these pathological changes, offering precise quantification of LV volumes, mass, and ejection fraction, as well as detailed myocardial tissue characterization (Table 4) [36]. Advanced CMR techniques, such as feature-tracking and tagging, further enhance assessment by measuring myocardial deformation, including global longitudinal strain

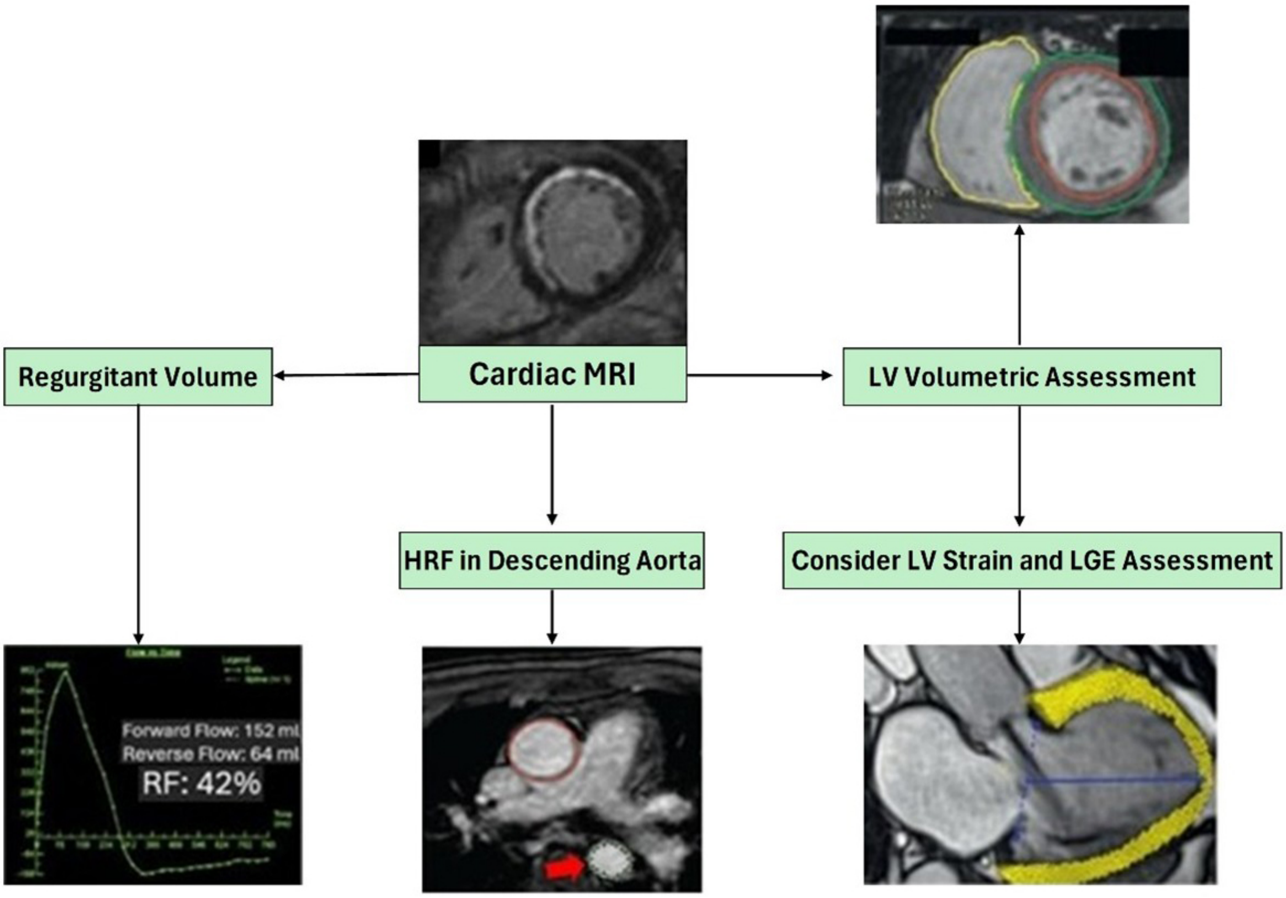

Fig. 2. The useful qualitative and quantitative CMR parameters in the assessment of native AR severity. Abbreviations: LV, left ventricle; LGE, late-gadolinium enhancement; HRF, holo-diastolic flow reversal; MRI, Magnetic resonance imaging; RF, Regurgitant fraction; CMR, Cardiac magnetic resonance imaging; AR, Aortic regurgitation.

(GLS) and circumferential strain. These strain parameters can detect subtle myocardial dysfunction not evident through conventional metrics, providing early indicators of ventricular impairment in AR patients [37].

Combined into one paragraph to improve flow.

CMR also provides tissue profiling with late gadolinium enhancement (LGE) and extracellular volume (ECV) quantification that evaluates for myocardial remodeling. LGE is the gold standard for detecting myocardial fibrosis noninvasively. Quantifying fibrosis burden via LGE MRI provides prognostic information, guiding therapeutic strategies and potentially influencing the timing of surgical intervention [37,38]. Malahfji *et al*. [39] investigated the relationship between myocardial scarring and mortality in chronic AR using CMR in 392 patients with moderate or severe AR for a follow-up period of up to 10.8 years. Malahfji *et al*. [39] found significantly higher mortality outcomes in patients with a myocardial scar, infarction scar, and non-infarction scar (hazard ratio (HR): 3.62, 4.94, and 2.75, respectively). Moreover, the myocardial scarring was independently associated with a 2.5-fold increase in risk of mortality. Fortunately, aortic valve replacement was associated with reduced mortality risk with an HR of 0.34 in patients with scarring. Conversely, detecting LGE as a surrogate for myocardial fibrosis using CMR predicts post-operative LV recovery and allows the identification of patients at high risk for worse post-surgical outcomes compared to those without LGE [40]. Considering the strengths of CMR and its reproducibility in evaluating ventricular volumes, tissue characteristics, and AR severity, CMR represents an excellent modality for serial measurements and longitudinal follow-up of patients with AR.

The combined use of MRI, echocardiography, and cardiac CT enhances the assessment of AR. Echocardiography provides real-time functional data, CT offers detailed anatomical visualization, and MRI adds precise tissue characterization and volumetric quantification [41]. Meanwhile, technological advances, such as 4D flow MRI and multimodality integration, are poised to refine AR evaluation further, enabling more accurate diagnoses, personalized treatment plans, and improved patient outcomes.

Future Perspectives of MRI in Aortic Regurgitation

The future of CMR in assessing valvular pathologies is promising. Over the next few years, several advances are likely to improve diagnosis and patient management based on the following observations:

(1) **Faster scanning techniques**: New techniques in MRI technology, such as compressed sensing and parallel imaging, will shorten scan times. These developments facilitate the treatment of patients and enhance the utility of MRI in the assessment of AR, thus making CMR easier to use [42].

(2) **Artificial intelligence (AI) integration**: The application of AI and machine learning algorithms in MRI analysis helps enhance image interpretation. AI can also be used to identify and measure abnormalities, increase diagnostic capabilities, and determine the disease risk by analyzing complex images [43].

(3) **4D flow MRI**: Four-dimensional flow MRI allows assessment of the dynamics of the 3D blood flow in space and time, thus providing extensive information on hemodynamics. This technique provides a clear view of the flow patterns associated with AR, enabling one to determine regurgitant volumes and the effects of the flow on the cardiac structures. Due to ongoing research on the clinical applicability of 4D flow MRI, this technology is anticipated to be established as a conventional tool for assessing AR [42]. Additionally, 4D flow MRI has been found to agree with echocardiography in grading AR, with high sensitivity and specificity when detecting more than mild regurgitation [44]. The ability of 4D flow MRI to provide detailed flow visualization and retrospective analysis of any flow type makes it a promising modality for improving the accuracy of AR quantification and potentially guiding treatment decisions [44,45].

Role of Artificial Intelligence in Aortic Regurgitation Imaging

Recent advancements in AI are transforming how AR is diagnosed, especially in complex cases. AI-powered tools now surpass traditional 2D echocardiography in assessing AR severity, achieving impressive agreement scores (κ = 0.94 vs. κ = 0.53) and accurately grading difficult cases, such as eccentric or multiple regurgitant jets, with 90% accuracy compared to just 30% using conventional methods [46]. Furthermore, deep learning models demonstrate strong potential for broader screening, with an area under the curve (AUC) of 0.84 in detecting AR and other valve conditions [35]. Beyond the diagnosis, these AI systems can automatically analyze patterns of ventricular remodeling, helping clinicians identify early signs of disease progression. Thus, by identifying subtle hemodynamic changes sooner, AI may support earlier surgical referrals, ultimately protecting patients from irreversible heart damage.

Management of AR

While surgical intervention remains the definitive treatment for AR, managing this condition is tailored through an individualized approach that integrates medical and surgical strategies. This approach is guided by the severity and progression of AR, ensuring optimal therapeutic outcomes.

Medical Management

Severe acute AR is a life-threatening condition that necessitates rapid hemodynamic stabilization. Intravenous diuretics and vasodilators can transiently control HF symptoms by decreasing the preload and afterload, respectively. However, these approaches provide only short-term relief, and surgery is, in fact, almost always required to treat the underlying reason.

Currently, there are no specific medical therapies approved to halt the progression or directly treat chronic AR. Additionally, management primarily focuses on symptomatic relief, including the use of diuretics for volume control and the treatment of concomitant hypertension.

First-line antihypertensive therapies for managing chronic AR include vasodilatory agents, such as angiotensin-converting enzyme (ACE) inhibitors, dihydropyridine calcium channel blockers, and hydralazine. These agents reduce systemic vascular resistance and help alleviate the hemodynamic burden of elevated stroke volume (SV). However, achieving effective blood pressure control in this patient population remains challenging due to the persistently high SV characteristic of chronic AR. Indeed, the pharmacological treatment of patients with Marfan syndrome using medications such as β-blockers or losartan has been reported to attenuate the rate of aortic root enlargement and, consequently, decrease the occurrence of deadly aortic complications. These drugs are also commonly prescribed for patients who have bicuspid aortic valves (BAVs) and related aortopathy [47,48].

Surgical Management

Prompt surgery in patients with acute severe AR is often lifesaving. Moreover, chronic severe AR requires careful timing of surgical intervention, guided by clinical guidelines based on parameters that predict poor outcomes if surgery is delayed (Table 5) [21,49]. Therefore, managing AR involves a comprehensive approach integrating clinical assessment with multimodality imaging to guide treatment decisions (Fig. 3). Initially, TTE was used as the primary imaging modality to assess AR severity and LV function [36,50]. If the TTE results are inconclusive or further evaluation is needed, then CMR can accurately quantify the regurgitant volume and regurgitant fraction to provide a detailed assessment of LV volumes and function

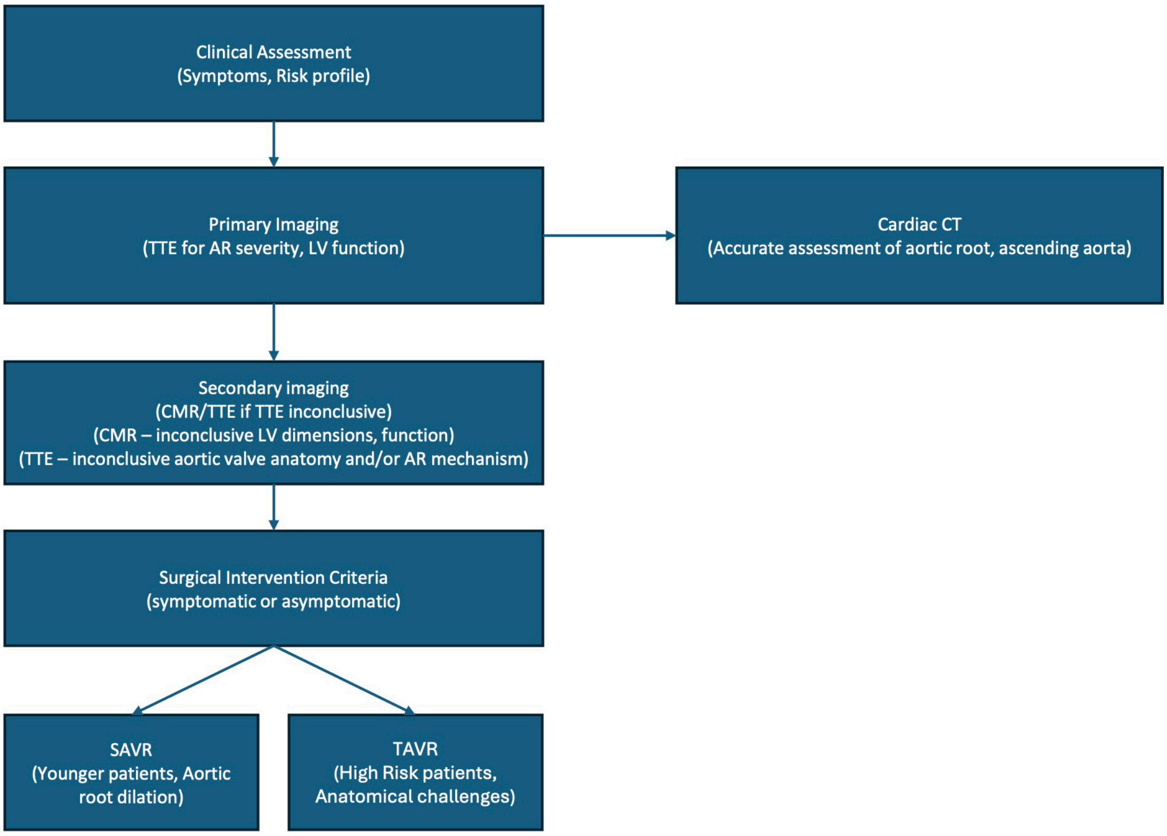

Fig. 3. Algorithm for multimodality cardiac imaging evaluation to guide treatment in aortic regurgitation. Abbreviations: CT, computed tomography; TTE, transthoracic echocardiogram; AR, aortic regurgitation; LV, left Ventricle; TEE, transesophageal echocardiogram; CMR, cardiac magnetic resonance imaging; SAVR, surgical aortic valve replacement; TAVR, transcutaneous aortic valve replacement.

Table 5. The 2020 ACC/AHA Guideline for managing patients with valvular heart disease and 2021 ESC/EACTS Guidelines for managing valvular heart disease.

Clinical scenario	ACC/AHA 2020	ESC 2021
Symptomatic severe AR (Stage D)	I B-NR	I B
Asymptomatic severe AR with LVEF ≤55% (C2)	I B-NR	LVEF ≤50%: I B
Severe AR undergoing other cardiac surgery	I C-EO	I C
Asymptomatic severe AR + LVESD >50 mm/>25 mm/m²	IIa B-NR	LVESD >50 mm/>25 mm/m²: I B
Moderate AR during cardiac/aortic surgery	IIa C-EO	IIa C
Progressive LVEF decline (55–60%) or LVEDD >65 mm	IIb B-NR	LVESD >20 mm/m² + low risk: IIb C
TAVI in isolated severe AR candidates	III (Harm) B-NR	Valve-sparing surgery recommended (I B)

Abbreviations: AR, aortic regurgitation; LVESD, left ventricular end-systolic diameter; LVEDD, left ventricular end-diastolic diameter; LVEF, left ventricular ejection fraction; TAVI, transcatheter aortic valve implantation; NR, non-randomized; EO, expert opinion.

[36,50]. CMR is particularly useful in cases where echocardiography data are inconsistent or incomplete [36].

Surgical intervention is recommended in symptomatic patients with severe AR, regardless of LV function [36]. Surgery is advised for asymptomatic patients if there is significant LV dysfunction (left ventricular ejection fraction (LVEF) ≤55%) or dilation (left ventricular end-systolic diameter (LVESD) >50 mm or left ventricular end-systolic dimension index (LVESDi) >25 mm/m^2) [36]. Recent evidence suggests that lower LV size and function thresholds might also warrant intervention, although these require further study [36]. Multimodality imaging helps identify patients who may benefit from early intervention by detecting early signs of LV remodeling and dysfunction [31]. For instance, a regurgitant fraction >33% on the CMR image has been associated with a higher likelihood of symptom progression and need for surgery [31].

Deciding between surgical aortic valve replacement (SAVR) and transcatheter aortic valve replacement (TAVR) depends on various factors, including the overall risk of the patient and the anatomy of the aortic valve. SAVR remains the gold standard, especially for younger patients or those with conditions such as aortic root dilation [51]. However, TAVR has become an option for patients who are considered high-risk surgical candidates or who present anatomical challenges, such as a large or elliptical annulus [51]. In these cases, multimodal imaging is key in this decision-making process. Echocardiography and CT scans help assess the structure of the aortic valve and surrounding areas, ensuring the right approach is chosen. Nonetheless, CT, in particular, is vital for measuring the aortic root and annulus to guarantee the proper fit of the valve prosthesis [51]. In more complex cases, CMR can provide additional clarity on the severity of AR and the condition of the LV, offering valuable insights to help guide the choice between SAVR and TAVR [50,52].

In asymptomatic patients with severe AR and stable LV function, regular monitoring for LV dilation or worsening EF is implemented periodically every six months [53]. Current guidelines recommend pre-emptive AV surgery (Class II indication) in asymptomatic patients with preserved LVEF in the setting of a significantly dilated LV. Paradoxically, higher indexed LVESD was associated with reduced longer-term mortality, likely because patients with dilated LV underwent AV surgery more frequently, which was associated with improved survival [7]. Recent evidence suggests that the natural history of asymptomatic severe AR may be less favorable than previously believed. Indeed, a recent study reported an annual mortality rate of 2.2% in individuals with a natural history of asymptomatic severe AR, which is significantly higher than the 0.2% per year reported in earlier studies. In a cohort of over 1400 patients followed for an average of 6.6 years, Alashi *et al.* [54] demonstrated that the LV dimension thresholds, above which the risk of mortality significantly increases, are substantially lower than those currently recommended by practice guidelines. Furthermore, asymptomatic or minimally symptomatic patients with severe AR who underwent aortic valve (AV) surgery experienced low in-hospital postoperative mortality rates (2% overall and 0.6% for isolated AV surgery). AV surgery was also associated with significantly improved long-term survival, independent of other established risk factors. Interestingly, higher indexed LV end-systolic dimensions (iLVESDs) were paradoxically linked to lower long-term mortality, as all patients with iLVESDs >2.5 cm/m^2 underwent AV surgery, which improved survival outcomes. Additionally, worsening LV strain (a maximum LV-GLS of –19%) in patients with severe AR and preserved LV function was independently associated with higher long-term mortality [54]. These findings underscore the need to redefine surgical intervention thresholds in asymptomatic patients with severe AR using cardiac multimodality imaging to optimize clinical outcomes. Notably, the optimal volumetric thresholds beyond which the risk of adverse events significantly increases are lower in older patients and women, highlighting the importance of tailored evaluation in these populations due to apparent sex and age differences in chronic LV remodeling [2].

Valve repair and valve-sparing operations now represent a viable alternative to valve replacement in dedicated centers of high expertise [55]. These methods are particularly beneficial in patients with BAVs or tricuspid valves when conditions such as cusp prolapse or aortic root dilation play a role in AR [53]. Aortic valve repair and valve-sparing surgeries show favorable long-term outcomes, with 10-year survival rates exceeding 80% and reoperation-free survival rates of 70–85% in patients with preserved ventricular function or appropriate cusp repair techniques [56,57]. Although valve repair has numerous advantages, it is not indicated in all patients, meaning patient candidacy should be based on their structural features, the pathological conditions of AR, and surgical capabilities. TAVR has become a promising option for managing AR, especially in patients who are at high surgical risk or deemed unsuitable for SAVR. Although TAVR has yet to be widely used for pure AR, recent evidence shows that certain populations increasingly rely on this technique. Analysis of health records in Germany from 2018 to 2020 revealed that TAVR is increasingly used for isolated AR, particularly in older patients with significant comorbidities [58]. Interestingly, the ongoing Align-AR trial is actively enrolling patients to undergo treatment for severe AR with the JenaValve Technology, which received Food and Drug Administration (FDA) approval for an investigational device exemption (IDE) trial to treat AR, with promising results [59].

Conclusions

Acute AR represents a medical emergency, whereas chronic AR exerts a progressive impact on the LV through combined pressure and volume overload, resulting in chronic remodeling, dilation, and eccentric hypertrophy. Advancements in multimodality cardiac imaging have enhanced the ability to evaluate the severity of native and prosthetic AR across various clinical scenarios, providing valuable prognostic insights and facilitating timely interventions to optimize patient outcomes. However, emerging evidence underscores the need to re-evaluate thresholds for surgical intervention in severe AR, with recent studies elucidating the influence of age and sex on AR prognosis. Integrating imaging with a multiparametric approach in evaluating AR underscores the critical importance of timely intervention, highlighting the clinical relevance of imaging findings in everyday practice.

Author Contributions

AG, TW: Contributed to manuscript planning, delegation, writing, revision, and approval of manuscript. JR, AA, EH, MS, GM: Contributed to manuscript planning, writing, revision, and approval of manuscript. All authors have participated sufficiently in the work. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

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Conflict of Interest

The authors declare no conflict of interest.

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