Cardiovascular Magnetic Resonance in Right Heart and Pulmonary Circulation Disorders

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KEYWORDS

• Cardiac magnetic resonance • Right heart and pulmonary circulation disorders • Diagnosis • Prognosis • Therapeutic management

KEY POINTS

- Cardiac magnetic resonance (CMR) allows accurate multiplanar assessment of right ventricle (RV) volume, global and regional systolic function, tissue characterization, and evaluation of right heart and pulmonary artery blood flows.
- The aim of this paper is to review the role of CMR in RV pressure-overload and volume-overload disorders and RV cardiomyopathies.
- The clinical utility of CMR in diagnosis, prognosis, and therapeutic management of the right heart and pulmonary circulation disorders is discussed.

INTRODUCTION

Cardiac magnetic resonance (CMR) provides a noninvasive morphologic and functional assessment, tissue characterization, and blood flow evaluation of the right heart and pulmonary circulation.[1]

Right heart and pulmonary circulation disorders are generally caused by right ventricle (RV) pressure overload, volume overload, and cardiomyopathy and they are associated with distinct clinical courses and therapeutic approaches, although they often may coexist.[2]

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This paper reviews CMR application in imaging of the right heart and pulmonary circulation and discusses its current and future application for the management of patients with right heart and pulmonary circulation disorders.

THE NORMAL RIGHT HEART AND PULMONARY CIRCULATION

The RV appears crescent shaped in cross-section, so it cannot be characterized using geometric assumptions. In normal conditions, the interventricular septum is concave toward the left ventricle (LV) throughout the cardiac cycle (Fig. 1).[2,3] The RV can be described in terms of the inlet region, the trabeculated apical myocardium and the infundibulum or RV outflow tract (RVOT).[2,3] The RV free wall is thinner than the LV wall.[2,3] The superficial RV wall layer is composed of myocardial fibers arranged more circumferentially than in the LV and it is responsible for inward contraction. The subendocardial RV layer is composed of preferentially arranged longitudinal myocardial fibers that causes systolic contraction of the base toward the apex. Shortening of the RV is greater longitudinally (75% of RV contraction) than radially, and twisting and rotational movements do not contribute significantly to contraction.[2,3] The RV and LV are closely interrelated through the septum, epicardial circumferential myocytes, and the pericardial space, which are the anatomic basis for biventricular functional interdependence. RV is more compliant of accommodating increased preload, but has heightened sensitivity to afterload change (it is unable to cope with brisk increments in pulmonary artery [PA] pressures).[2,3]

THE ROLE OF CARDIAC MAGNETIC RESONANCE

Strengths and weakness of imaging modalities in the evaluation of structure and function of right heart and pulmonary circulation unit are illustrated in Table 1.[1,4–6]

CMR is the gold standard modality for noninvasive RV imaging. It allows multiplanar imaging of the RV, gives accurate quantitative assessment of several parameters (ventricular volumes, myocardial mass, ejection fraction [EF], stroke volume [SV], and cardiac output [CO]), and qualitative assessment of RV regional function with a low intraobserver and interobserver variability and good interstudy reproducibility.[5,6] CMR allows also tissue characterization and evaluation of vascular abnormalities.[1,5,6] Limitations of CMR may include low availability, high cost, breath hold requirement, claustrophobia, safety in patients with ferromagnetic implants, and use of gadolinium in patients with severe chronic renal failure.[1]

CARDIAC MAGNETIC RESONANCE IMAGING PROTOCOL

Routine CMR scans include cine, phase contrast (PC), and postcontrast sequences. For cine imaging, balanced steady-state free precession (b-SSFP) is the sequence of choice for assessment of LV and RV size and function due to its excellent contrast-to-noise ratio between cardiac structures and high reproducibility and reliability. Stacks of cardiac short-axis and transaxial images are acquired for a complete volumetric coverage of the RV.[7] Also, PC imaging of PA, including main (MPA), right (RPA), and left (LPA), can be obtained to assess PA hemodynamic variables and dimensions. Using this technique, pulmonary flow (QP) and systemic flow (QS) ratio and valve regurgitation severity can be quantified. Then, contrast-enhanced magnetic resonance angiography (ce-MRA) allows accurate visualization of central, lobar, and segmental pulmonary vessels. In patients for whom gadolinium is contraindicated, 3D whole-heart MRA (or 3D-SSFP) can be used instead. Finally, late gadolinium enhancement (LGE) imaging, obtained 10 to 15 min after administration of intravenous gadolinium contrast agent,

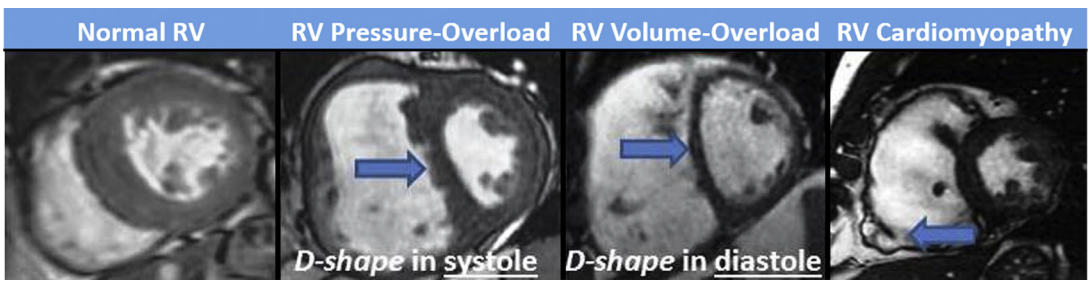

Fig. 1. Normal RV (normal RV dimension and septum concave toward LV), RV pressure-overload (RV hypertrophy and D shape of LV in "systole"), RV volume-overload (RV dilatation and D shape of LV in "diastole"), RV arrhythmogenic cardiomyopathy (RV dilatation and aneurysms). LV, left ventricle; RV, right ventricle.

Table 1
Relative strengths and weaknesses of different multimodality imaging techniques in the evaluation of structure and function of right heart and pulmonary circulation

	Echo	CMR	CT	Nuclear Imaging
Availability	++++	++	+++	++
Portability	++++	–	–	–
Cost	Low	High	Medium	Medium
Speed of acquisition	++++	++	++++	+
Radiation risk	–	–	+++[a]	++++
Suitability for sick or claustrophobic patients	++++	+	++	+/–
Contrast agents	+/–	+	++++	–
Temporal resolution	++++	+++	++	–[b]
Spatial resolution	++	+++	++++	+
Right heart structure	+++	++++	++	–
Right ventricular function	+++	++++	++	++
Tissue characterization	+	++++	++	+
Myocardial viability	+	++++	+	++++
First-pass perfusion	++	++++	–	++++
Coronary artery imaging	+	++	+++	–
Assessment of pressure gradients	++++	++	–	–
Clinical application	• Allows to assess right heart structure, function, and pressures at rest and during exercise • 2D echo can be used as a screening tool • 3D echo is more accurate and reproducible in evaluating RV size and systolic function	• Is the gold standard in evaluating right heart structure and function • Allows tissue characterization and evaluation of vascular abnormalities • Ruling out underlying CAD	• Allows quantitative 3D RV assessment and fatty infiltration when CMR is unavailable or unsuitable • Ruling out underlying CAD and lung disease (interstitial, COPD, CTEPH, cancer)	• Allows assessment of myocardial ischemia and viability in underlying suspected CAD

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Table 1
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	Echo	CMR	CT	Nuclear Imaging
Limitations	• Highly operator dependent • Inadequate imaging window • Limited evaluation of right ventricle and pulmonary circulation	• Safety in patients with ferromagnetic implants • Use of gadolinium in patients with severe chronic renal failure • Breath holding • No portability • Higher cost • Claustrophobia	• Radiation exposure • Use of iodinated contrast • No portability • Higher cost • Claustrophobia	• Radiation exposure • No portability • Low spatial resolution • Long scanning time • Significantly higher cost

+ denotes a positive remark and − denotes a negative remark. The number of signs indicates the estimated potential value.

Abbreviations: CAD, coronary artery disease; CMR, cardiovascular magnetic resonance; COPD, chronic obstructive pulmonary disease; CT, computed tomography; CTEPH, chronic thromboembolic pulmonary hypertension; RV, right ventricle.

[a] Radiation risk is significantly higher when the cine ventricular function and fist pass perfusion are performed.

[b] Temporal resolution for nuclear techniques is variable and depends on the radiotracer and counts.

Modified from Zhou X, Ferrara F, Contaldi C, et al. Right ventricular size and function in chronic heart failure: not to be forgotten. Heart Fail Clin 2019;15:210; with permission.

permits visualization and quantification of myocardial reparative fibrosis (scar).[5,6] When indicated, other optional CMR techniques can be used (Table 2).

PRESSURE-OVERLOAD DISORDERS

RV pressure overload leads to RV hypertrophy, predominantly end-systolic and early-diastolic flattening of the interventricular septum and "D shape" of the LV in systole (see Fig. 1). In the setting of chronic pressure overload, the RV initially responds with preserved volumes and function and compensatory "concentric" hypertrophy, successively, with "eccentric" hypertrophy, progressive RV dilatation, dyssynchrony, fibrosis, and reduced CO, leading to deterioration of exercise capacity and ultimately clinical decompensation. The RV becomes less dependent on longitudinal shortening.[2] The most common chronic RV pressure-overload disorders are described in the following paragraphs.

Table 2
Cardiac magnetic resonance protocol for right heart and pulmonary circulation

Technique	Information
CINE (b-SSFP)	• RV and LV dimension, mass, regional and global function • Atrial dimension • Interventricular septal changes • MPA, LPA, RPA dimension • Pulmonary valve direct planimetry
Phase contrast	• QP and QS • Cardiac output and PA flow profile • Pulmonary valve direct regurgitant volume • PA stiffness and pulsatility
LGE	• Ventricular myocardial reparative fibrosis • Ventricular myocardial microvascular obstruction
ce-MRA	• Vascular anatomy • Pulmonary perfusion
3D whole-heart MRA or 3D SSFP	• Vascular anatomy
Black blood images with and without fat suppression (when indicated)	• Fat infiltration
T2w STIR (when indicated)	• Myocardial edema • Myocardial hemorrhage
T1-Mapping (optional)	• Diffuse myocardial fibrosis
T2-Mapping (optional)	• Myocardial edema
Tagging technique/feature tracking (optional)	• Strain and strain rate analysis • Interventricular asynchrony
4D Flow (optional)	• RV and PA 3D flow patterns • PA vortex • PA wall shear stress and energy loss • RV kinetic energy work density

Abbreviations: b-SSFP, balanced steady-state free precession; ce-MRA, contrast-enhanced magnetic resonance angiography; LPA, left pulmonary artery; LV, left ventricle; MPA, main pulmonary artery; PA, pulmonary artery; QP, pulmonary flow; QS, systemic flow; RPA, right pulmonary artery; RV, right ventricle.

Pulmonary Hypertension

Pulmonary hypertension (PH) is a pathophysiological condition defined as an increase in mean PA pressure (mPAP) ≥25 mm Hg at rest by right heart catheterization (RHC). It is hemodynamically categorized into 2 groups: precapillary and postcapillary. In particular, pulmonary arterial hypertension (PAH) is defined as a group of precapillary PH and pulmonary vascular resistance (PVR) >3 Wood units in absence of the other causes of precapillary PH.[8] The PH diagnostic algorithm with the specific role of noninvasive imaging is illustrated in **Fig. 2**.

ROLE OF CARDIAC MAGNETIC RESONANCE IN PULMONARY HYPERTENSION

Diagnosis and Cause

The most accurate tools by cine-CMR, for the identification of PH are the ventricular mass index, which expresses the degree of chronic RV pressure overload,[9] the increased area and thickness of basal segment of the septomarginal band,[10] and the interventricular septum curvature ratio, which is an accurate and reproducible index of RV systolic pressure.[11] Cine-CMR also allows visualization of the degree of flattening of the interventricular septum and a "D-shaped" LV in the presence of severe PH (see **Fig. 1**).[2]

Using 2D-PC, peak PA systolic pressure can be derived using the modified Bernoulli equation and reduced pulmonary average velocities, blood flow, and distensibility can be evaluated in patients with PH.[12] Average velocity in the MPA has a high degree of reliability in detecting PH and it has also a strong inverse correlation with PAP and PVR.[13] Relative area change (RAC) can be used as a marker of MPA stiffness. RAC increases early in PH and may detect exercise-induced PH before overt pressure increases occur at rest.[14]

LGE-CMR shows areas of LGE induced by chronic ventricular overload frequently in the RV insertion points of the interventricular septum corresponding to higher fiber stress zones (**Fig. 3**, **Table 3**).[15,16] However, no single CMR parameter can exclude PH.

In identifying the cause of PH due to left heart disease, CMR can quantify LV volumes and EF accurately, identify valvular heart disease, and differentiate between ischemic and nonischemic cardiomyopathy by the pattern of LGE.[1] If coronary artery disease is suspected, stress perfusion CMR can evaluate LV and RV function, perfusion, and myocardial scar. In chronic thromboembolic PH, ce-MRA may allow accurate visualization of the lobar and segmental pulmonary vessels, and 3D whole-heart MRA may measure regional changes in segmental or subsegmental lung perfusion.[1,5,6] In patients with PAH secondary to congenital heart disease, CMR provides complete evaluation of cardiac and extracardiac structures and may be useful in diagnosis, treatment planning and follow-up[5,6] (see **Fig. 2**).

Risk Stratification, Prognosis, and Monitor Treatment Efficacy

Cine-CMR is useful in clinical management. An increased RV end-diastolic volume (EDV) indexed to body surface area (RV EDVI) is the most reliable marker for RV failure and a valuable predictor of poor survival. The correlation of RV dilatation to mortality is stronger than RV hypertrophy[17]; however, ventricular mass index has been suggested to be a predictor of decreased survival.[18] RV EF is the strongest predictor of mortality[19,20] and severity of right atrial (RA) volume dilation is associated with disease progression and prognosis.[21,22] PC-CMR measurements reflecting stiffness of the proximal pulmonary vasculature[23] are independent predictors of outcome. LGE at the RV insertion point seems to be associated with more advanced PH, especially if the LGE is including the septum (**Table 4**).[16,24]

For the monitoring of drug therapy in patients with PH, RV mass and RV EF by cine-CMR might be used.[19,25] In patients with PH, the addition of sildenafil to bosentan therapy reduces RV mass and this effect is associated with improvements of symptoms and NT-proBNP[25]; after 1 year of therapy, reduced RV EF is associated with poor outcome, even in patients with PAH with PVR improvement[19] (**Table 5**).

NOVEL CARDIAC MAGNETIC RESONANCE TECHNIQUES IN PULMONARY HYPERTENSION

T1-Mapping

T1-mapping has been developed to quantify diffuse myocardial fibrosis directly measuring the T1 relaxation times. Native T1 reflects both the intracellular and extracellular compartments.[26] The extracellular contrast volume (ECV) (calculated taking into account myocardial and blood T1 values precontrast and postcontrast) provides a direct measure of the of myocardium occupied by extracellular space.[26]

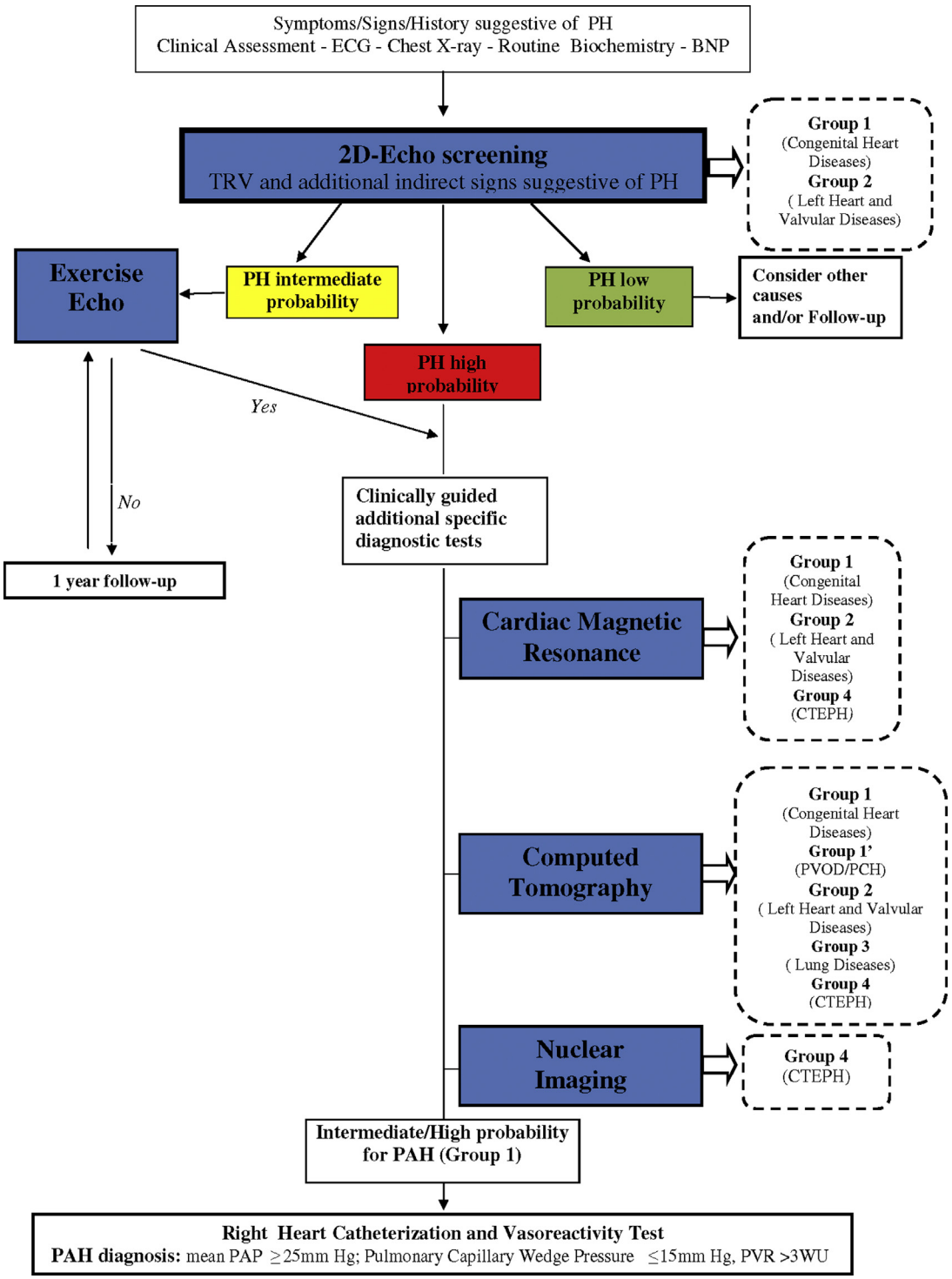

Fig. 2. Flowchart of PH diagnostic algorithm with the specific role of noninvasive imaging. CTEPH, chronic thromboembolic pulmonary hypertension; PAH, pulmonary arterial hypertension; PAP, pulmonary artery pressure; PCH, pulmonary capillary hemangiomatosis; PH, pulmonary hypertension; PVOD, pulmonary veno-occlusive disease; PVR, pulmonary vascular resistance; TRV, transtricuspid valve regurgitation velocity; WU, Wood units.

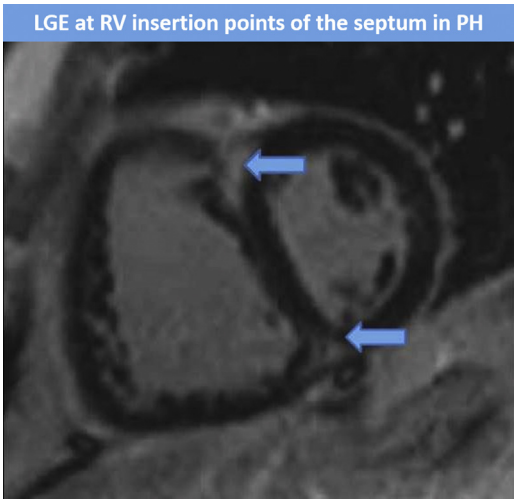

Fig. 3. An example of LGE (*blue arrows*) at RV insertion point spreading into the septum in a patient with PH. LGE, late gadolinium enhancement; PH, pulmonary hypertension; RV, right ventricle.

In patients with precapillary PH, native T1 values of RV insertion points are significantly increased and are related to PH severity.[27] In patients with PH, RV ECV is increased. Both native T1 and ECV values at RV insertion points are increased and show significant correlations with pulmonary hemodynamics, RV arterial coupling, and RV performance. ECV is increased before overt RV systolic dysfunction.[28] ECV is useful in detecting myocardial involvement in early stages of PH, can guide management, and serve as a therapeutic target. However, caution should be emphasized in interpreting T1 values in the thin and highly trabeculated RV free wall, as partial volume effects and inclusion of fat or blood (erroneously, however easily done) in the region of interest are major caveats to the measurements.

Strain Analysis

Fast strain encoded (SENC) is a through-plane CMR-tagging technique that allows direct

Table 3
The main cardiac magnetic resonance diagnostic parameters in pulmonary hypertension

Diagnostic CMR Variable	Cutoff Value	Detection of PH		Reference
		Sensitivity (%)	Specificity (%)	
Cine-CMR				
VMI (RV mass/LV mass)	≥0.4	81	88	Swift et al,[9] 2012
LV septal to free wall curvature ratio	≤0.67	87	100	Dellegrottaglie et al,[11] 2007
RV EDVI	≥75 mL/m^2	67	50	Swift et al,[9] 2012
RV mass index	≥20 g/m^2	83	84	Swift et al,[9] 2012
RV EF	≤35%	67	71	Swift et al,[9] 2012
RV RAC	≤30%	61	81	Swift et al,[9] 2012
TAPSE	≤2 cm	76	64	Swift et al,[9] 2012
PC-CMR				
PA RAC (max MPA CSA–min MPA CSA/min MPA CSA)	≥15%	84	74	Swift et al,[14] 2012
PA average velocity	<11.7 cm/s	93	82	Sanz et al,[13] 2007
Retrograde flow	≥0.3 L/min/m^2	83	71	Swift et al,[9] 2012
LGE-CMR				
RV insertion site LGE	Present	83	94	Swift et al,[9] 2012
4D-Flow-CMR				
MPA vortical blood flow (t_{vortex})[a]	≥14.3%	97	96	Reiter et al,[33] 2015

Abbreviations: CSA, cross-sectional area; EDVI, end-diastolic volume index; EF, ejection fraction; LV, left ventricle; MPA, main pulmonary artery; RAC, relative area change; RV, right ventricle; VMI, ventricular mass index.

[a] t_{vortex}: the percentage of cardiac phases with vortex present.

Modified from Swift AJ, Rajaram S, Condliffe R, et al. Diagnostic accuracy of cardiovascular magnetic resonance imaging of right ventricular morphology and function in the assessment of suspected pulmonary hypertension results from the ASPIRE registry. J Cardiovasc Magn Reson. 2012;14(1):40.

Table 4
The main cardiac magnetic resonance prognostic parameters in pulmonary hypertension

Prognostic CMR Variable	Cutoff Value	Comment	Reference
Cine-CMR			
RV EDVI	$\geq$84 mL/m^2	Predictor of RV failure and mortality	Van Wolferen et al,[17] 2007
RV EF	$\leq$35%	Predictor of poor outcome and mortality	van de Veerdonk et al,[19] 2011
Ventricular mass index (RV end-diastolic mass/LV end-diastolic mass)	$\geq$0.7	Predictor of decreased 2-y survival	Hagger et al,[18] 2009
RA volume	Increased	Associated with disease progression and prognosis	Sato et al,[21] 2013
PC-CMR			
Pulmonary artery relative area change	$\leq$16%	Predictor of poor outcome and mortality	Gan et al,[23] 2007
SVI	$\leq$25 mL/m^2	Predictor of RV failure and mortality	Van Wolferen et al,[17] 2007
LGE-CMR			
RV insertion site LGE	Present	Predictor of poor prognosis	Freed et al,[16] 2012
Feature tracking CMR			
RV GLS and GLSR	Reduced	Associated with poor outcome	Menezes de Siqueira et al,[30] 2016
RV GCSR	$> -0.8\ s^{-1}$	Predictor of events	Menezes de Siqueira et al,[30] 2016
LV GLS	$> -14.2\%$	Predictor of poor outcome and mortality in precapillary PH	Padervinskienė et al,[31] 2019

Abbreviations: EDVI, end-diastolic volume index; EF, ejection fraction; GCSR, global circumferential strain rate; GLS, global longitudinal strain; GLSR, global longitudinal strain rate; LV, left ventricle; RV, right ventricle; SVI, stroke volume index.

measurement of regional function by using a free-breathing single-heartbeat real-time acquisition. It allows direct measurement of longitudinal strain by using short-axis images. Fast SENC identifies significantly reduced RV longitudinal contractility at basal-mid anterior septal insertions and mid anterior RV wall in patients with PAH with normal global RV function.[29]

Feature tracking (FT) is a novel method that allows quantification of myocardial deformation from cine-CMR images. Patients with PH show significant reductions in global longitudinal strain (GLS), global circumferential strain (GCS), global longitudinal strain rate (GLSR), and global circumferential strain rate (GCSR). GLS, GLSR, and GCSR are independently associated with outcome.[30] LV GLS also shows correlation with RV dysfunction and is associated with poor clinical outcome and mortality.[31] Therefore, in PH, quantification of RV and LV strain by FT-CMR is feasible, correlates with disease severity, and is independently associated with poor outcome (see **Table 4**).

Blood Flow Imaging

4D Flow CMR is an evolving imaging technique that provides in-vivo assessment of 3-directional blood flow within 3D vascular structures throughout the cardiac cycle. RV volume, function, and mass can be quantified with interobserver agreement comparable with cine-CMR SSFP sequences.[32] Whole-heart 4D flow CMR enables detection and visualization of both normal and abnormal right heart flow patterns. In patients with PH, vortex of blood flow in the MPA from 4D flow CMR is present and the vortex duration has been related with mPAP (**Fig. 4**, see **Table 3**).[33] Vorticity is decreased in the RPA of patients with PH and it correlates with an increase in PVR.[34] 4D flow CMR can also estimate wall shear stress (WSS), a measure of viscous hemodynamic forces

Table 5
Role of cardiac magnetic resonance in right heart and pulmonary circulation disorders

Pulmonary Hypertension	Pulmonary Valve Stenosis	Tricuspid Valve Regurgitation	Pulmonary Valve Regurgitation	Systemic-to-Pulmonary Shunt	RV Infarction	Arrhythmogenic Cardiomyopathy	Other Nonischemic Cardiomyopathies *(Hypertrophy, Dilated, Noncompaction, Tako-Tsubo, Amyloidosis, Sarcoidosis, Myocarditis)*
Diagnosis	Accurate assessment of valve stenosis severity: prefer *planimetry*	Accurate assessment of valve regurgitation severity: prefer *indirect method*	Accurate assessment of valve regurgitation severity: prefer *direct method*	Size, location, and number of communications between pulmonary and systemic circulations: *intra- and extracardiac*	Evaluation of RV ischemic injury: • RV anatomic and functional assessment • Tissue characterization	Early diagnosis	Early RV/LV involvement
Cause	Hemodynamic consequences	Hemodynamic consequences	Hemodynamic consequences	Hemodynamic consequences	RV infarction complications	Disease classification	Prognosis
Prognosis	Identify sub- or supravalvular stenosis	Prognosis	Prognosis	Accurate QP/QS ratio quantification	Prognosis	Prognosis	Detection of eventual associated systemic alterations, ie, enlarged lymph nodes
Monitor treatment efficacy	Secondary PA dilatation		Timing of reintervention: in previous surgery for congenital heart diseases	Atrial septal defect rims		Follow-up in *definite, borderline, or possible arrhythmogenic cardiomyopathy*	

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	Guidance to pulmonic valvuloplasty-valve replacement	Indication to pulmonary valve replacement	Family screening
Indication to percutaneous valve treatment			Differential diagnosis

Abbreviations: LV, left ventricle; PA, pulmonary artery; RV, right ventricle; QP, pulmonary flow; QS, systolic flow.

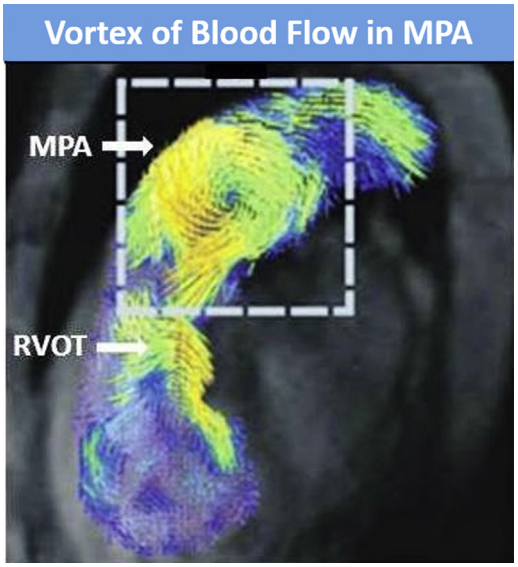

Fig. 4. An example of a vortex of blood flow in the MPA in a patient with PH by 4D flow CMR. CMR, cardiac magnetic resonance; MPA, main pulmonary artery; PH, pulmonary hypertension.

acting on the vessel walls (risk factor of endothelial degeneration) and energy loss (EL), the energy dissipation caused by abnormal 3D blood flow (associated with high cardiac workload) in aortic disease.[35] EL is a possible predictor of heart failure.[36] In patients with PH, 4D flow CMR at the MPA, RPA, and LPA shows significantly lower WSS, independent of the 4D flow CMR acquisition strategy.[37] In addition, PA WSS is reduced in both children and adults with PAH associated with the degree of vessel dilation and stiffness. EL, instead, is increased in PAH without difference between adults and pediatric patients.[38] In patients with PAH, increase in RV kinetic energy work density and in PA percent EL seem to be promising markers for RV dysfunction.[39]

Computational fluid dynamics (CFD) modeling, is another novel technology that generates equations of fluid dynamics in a computer using patient-specific vascular or heart chambers geometries and physiologic flow or pressure conditions. The geometries are reconstructed from segmentation of CMR or computed tomography (CT) images (**Fig. 5**). This technique has high temporal and spatial resolution and can also be used to reproduce the virtual flow that would be realized in hypothetical postsurgical conditions, therefore adding predictive capabilities to modern flow imaging.[40] A CFD combined with CMR study has demonstrated for the first time that WSS is altered in PAH, showing reduced WSS in the proximal PAs, as reported successively by 4D flow CMR.[41] The prognostic value of these novel technologies for blood flow imaging remain to be proven; however, in the future they could offer a noninvasive alternative to RHC and could help in early detection of PH.

FUTURE PERSPECTIVES OF CARDIAC MAGNETIC RESONANCE IN PULMONARY HYPERTENSION

Exercise Cardiac Magnetic Resonance

CMR during exercise permits highly reproducible and accurate measurements of RV volumes and function, and CO is comparable with that obtained by the direct Fick method.[42] Assessment of RV function with CMR during exercise stratifies patients with PAH currently perceived as having a low risk of mortality into different degrees of RV inotropic reserve. Reduced RV SV during exercise CMR is a plausible marker of increased risk of decompensation, possibly warranting targeted therapy intensification to restore RV functional reserve.[43]

CMR during exercise is currently performed in very few centers because of difficulties in running adequate exercise sessions in the magnetic resonance environment.

Cardiac Magnetic Resonance-Guided Right Heart Catheterization

CMR-guided RHC (CMR-RHC) can combine the benefits of CMR and invasive cardiac catheterization.

CMR-RHC, using passive catheters, is an attractive modality for comprehensive hemodynamic characterization of cardiovascular conditions, such as PAH. After baseline CMR for cardiac function, transfemoral catheters are navigated into the superior vena cava (SVC), and thereafter from the right atrium into the RV and one or both pulmonary arteries. Patients with suspected PAH can be screened using first-pass contrast lung perfusion. Procedure time increases with worsening PAH.[44,45] CMR-RHC applications are still in the primordial phase of clinical application, with few advanced centers equipped with hybrid-invasive CMR facilities. However, in the future CMR-RHC might be incorporated into routine clinical practice for the investigation of PAH.

Pulmonary valve stenosis

Pulmonary valve stenosis (PS) is another cause of RV pressure overload and it is usually an isolated congenital abnormality but may be associated with other conditions (tetralogy of Fallot,

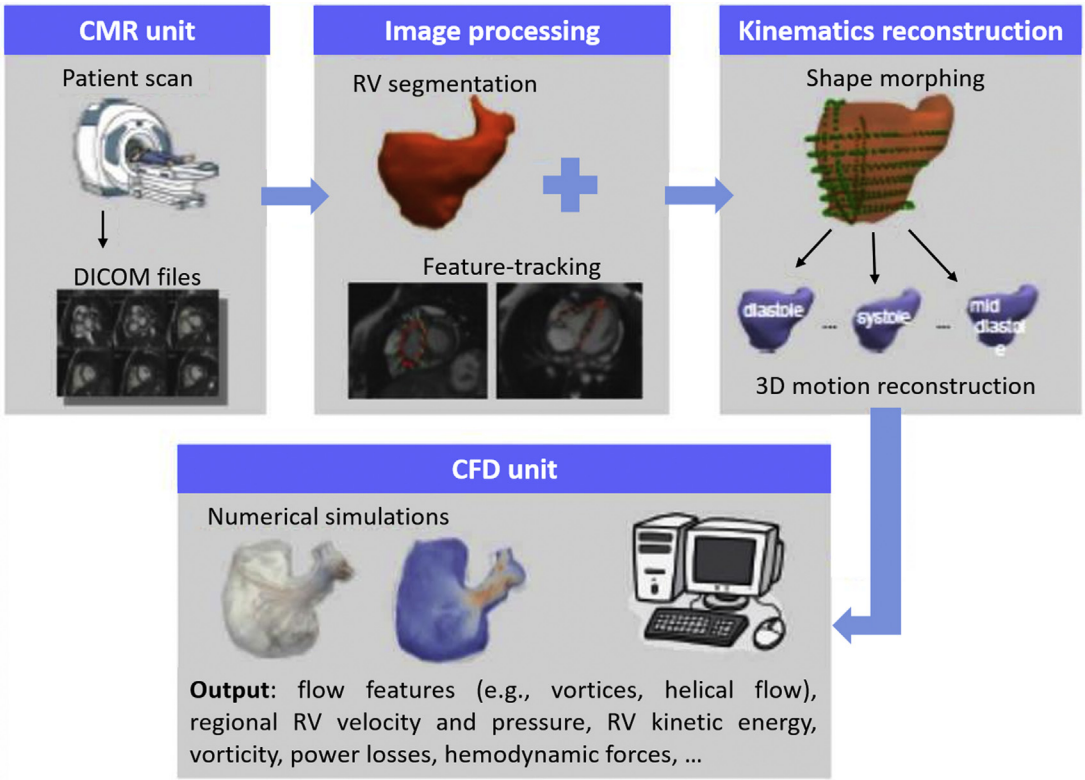

Fig. 5. A workflow from clinical imaging to numerical simulation of RV flow using CFD. (1) Acquisition of cine-CMR SSFP images; (2) FT-CMR to automatically extract the time evolution of the RV endocardium and a fine 3D triangulated surface mesh of the geometry of the RV obtained through a segmentation process; (3) reconstruction of 3D RV motion using an image registration technique; (4) numerical simulations performed using CFD to solve the flow equations inside the previously computed moving geometry. CFD, computational fluid dynamics; CMR, cardiac magnetic resonance; FT-CMR, feature tracking cardiac magnetic resonance; RV, right ventricle; SSFP, steady-state free precession.

congenital rubella, and Noonan syndrome). PS may be secondary to carcinoid syndrome, rheumatic heart disease, thrombus, or cardiac surgery. PS is also associated with secondary dilation of MPA and LPA (less so the RPA) and with abnormalities of the structure of PA wall.[46,47]

ROLE OF CARDIAC MAGNETIC RESONANCE IN PULMONARY VALVE STENOSIS

Imaging the pulmonary valve requires an RVOT view and potentially a second view perpendicular to this plane.[46–48] Cine-CMR shows doming of the leaflets, a high-velocity jet across the pulmonary valve and subvalvular or supravalvular stenosis. Short-axis cine imaging through the valve tips in systole provides direct planimetry of the valve orifice for accurate determination of anatomic orifice area. Multiple parallel thin slices may be helpful to locate the optimal slice. Cine-CMR can also quantify the hemodynamic consequences of PS.[46,48] PC-CMR quantifies the peak velocity and the peak gradient is calculated using the modified Bernoulli equation.[48] CMR can also provide a functional/effective orifice area (similar to the continuity equation by echocardiography), but direct planimetry is usually more reliable.[47] CMR can be useful to select patients eligible for percutaneous valve replacement. Valvuloplasty and valve replacement may be performed under CMR guidance (see **Table 5**).[47]

VOLUME-OVERLOAD DISORDERS

RV volume overload leads to RV dilatation and hypertrophy with increased free wall mass but preserved thickness and predominantly diastolic leftward septal shift with “D shape” of LV in diastole (see **Fig. 1**). In the setting of chronic volume overload, RV contractility remains preserved for long time periods, although contractile reserve may be compromised.[2,3] The most common RV

volume-overload disorders[2,3,48–51] are listed in Table 6.

ROLE OF CARDIAC MAGNETIC RESONANCE IN VOLUME-OVERLOAD CONDITIONS

Tricuspid Valve Regurgitation

CMR can provide accurate assessment of tricuspid valve regurgitation (TR) severity and its secondary hemodynamic consequences and also identify RV dysfunction. Standard long-axis cine-CMR views with additional thin image slices positioned perpendicular to the leaflet sections may help to visualize the detailed anatomy/function. PC-CMR in-plane is helpful to identify the regurgitant jet. CMR allows quantitation of *regurgitant volume* and *regurgitant fraction.*[48] The *regurgitant volume* is usually calculated indirectly, subtracting the flow volume by PC-CMR in the MPA from the SV obtained by cine-CMR-derived RV volume measurements. Direct measurement of regurgitant flow at the valve is feasible but difficult due to mobile valve leaflets and high-velocity jets. An increased RV EDV by cine-CMR can predict RV dysfunction at follow-up[48–50] (see Table 5).

Table 6
Definition and classification of the most common right ventricle volume-overload disorders

			Systemic-to-Pulmonary Shunt	
	Tricuspid Valve Regurgitation	**Pulmonary Valve Regurgitation**	**Atrial Septal Defect (ASD)**	**Partial Anomalous Pulmonary Vein Drainage (PAPVC)**
Definition	Blood flows back through the tricuspid valve *Tricuspid valve complex:* large tricuspid annulus, 3 leaflets (anterior, posterior, and septal), 3 independent papillary muscles, and chordae tendineae	Blood flows back through the pulmonary valve *Pulmonary valve:* 3 semilunar leaflets (anterior, left, and right)	Defect in the interatrial septum	Anomalous connection of 1 or more pulmonary veins to the systemic venous system
Classification	Primary anatomic valvular problems: • Iatrogenic • Endocarditis • Rheumatic valve disease • Carcinoid • Congenital heart disease (ie, Ebstein anomaly) Functional (more common): • Annular dilatation due to RA and/or RV dilatation and papillary muscle displacement	Native valve (rare) Primary anatomic problems: • Endocarditis • Carcinoid Secondary to: • Surgical valvotomy/valvectomy or balloon pulmonary valvuloplasty for pulmonary stenosis (eg, tetralogy of Fallot) Functional: • PA dilatation • Severe PAH	Ostium secundum (80%) *Ostium primum (15%):* ± atrioventricular valve defects Sinus venous (5%): • Near the SVC • ± PAPVC (ie, upper right PV in SVC or RA) Coronary sinus (<1%)	The first most common type: • Right upper and middle PV into SVC • Often + superior sinus venosus ASD The second most common type: • Left upper PV into the left innominate vein via a vertical vein Scimitar syndrome: • All right-sided PVs into RA, IVC or hepatic veins

Abbreviations: IVC, inferior vena cava; PA, pulmonary artery; PAH, pulmonary arterial hypertension; PV, pulmonary vein; RA, right atrium; RV, right ventricle; SVC, superior vena cava.

Pulmonary Valve Regurgitation

CMR is the most accurate method for quantifying pulmonary valve regurgitation (PR) and its secondary hemodynamic consequences, and it plays a crucial role in the timing of reintervention in patients with previous surgery for congenital heart diseases (ie, tetralogy of Fallot). Cine-CMR can show a dark jet of dephasing during diastole extending into the RVOT. PC-CMR quantifies PR using a through-plane positioned just above the valve and the measurement of regurgitant volume is usually direct (Fig. 6). The regurgitant volume or regurgitant fraction and RV EDV have been shown to be highly predictive of the development of symptoms and the need for surgery[46,48,51] (see Table 5).

Systemic-to-Pulmonary Shunt

Cine-CMR can provide intracardiac and extracardiac anatomy, size, location, and number of communications between pulmonary and systemic circulations, ventricular volumes and function, and PA dimensions. In atrial septal defect (ASD), cine-CMR can show low-intensity flow jets between the atria. SSFP images in multiple axial and short-axis planes perpendicular to ASD provide an assessment of the defect location and size throughout the cardiac cycle. PC-CMR is the noninvasive gold standard for quantifying QP and QS, independent of the location of the shunt.[48,51] In a PC-cine acquisition with a very low velocity-encoding limit, the flow via the ASD can lead to aliasing and clear demarcation of the defect, allowing measurement of the ASD rims for evaluation of eligibility to percutaneous closure. Ce-MRA details extracardiac shunts[48,51] (see Table 5).

RIGHT VENTRICLE CARDIOMYOPATHIES

Right Ventricle Infarction

The RV can be involved frequently in inferior acute myocardial infarction (AMI) (up to 50%) and less often in anterior AMI. Isolated RV AMI is rare (<3%). The RV is more resistant to prolonged ischemia than the LV thanks to its more favorable oxygen demand/supply profile; however, lack of RV recovery is associated with persistent hemodynamic compromise and high mortality.[2]

Role of cardiac magnetic resonance in RV infarction

In RV infarction, CMR is clinically useful because it allows detailed anatomic and functional assessment of RV and provides tissue characterization. Axial and short-axis cine-CMR can assess accurately eventual increased RV volume, reduced EF, and regional function alterations. In acute RV infarction, T_2 STIR sequences can show RV edema and eventual hemorrhage. LGE-CMR can show, in the RV and frequently in the territory of right coronary artery, subendocardial or transmural LGE, microvascular obstruction (in the acute setting) (Fig. 7), and RV thrombi**.** LGE of the RV is feasible, but challenging as the RV wall is thin and may require a different time inversion than that used to assess LV LGE. RV LGE has strong prognostic relevance[52] (see Table 5).

Arrhythmogenic Cardiomyopathy

Arrhythmogenic cardiomyopathy (ARVC) is a genetically determined cardiomyopathy, characterized by the replacement of the ventricular myocardium by fibro-fatty tissue, from the epicardium toward the endocardium. The RV can be primarily affected with RV dilatation and altered regional and/or global function (see Fig. 1); however, the LV can also be involved, although LV dimensions or function can be normal. Isolated or predominant LV involvement can also be present, usually limited to the subepicardium or midmural layers of the posterolateral wall. ARVC can be a cause of sudden cardiac death due to ventricular fibrillation in young adults, so early diagnosis can be very important.[53,54]

Role of cardiac magnetic resonance in arrhythmogenic cardiomyopathy

CMR is the imaging modality of choice for early diagnosis of ARVC, as it allows RV multiplanar imaging and tissue characterization. Axial and short-axis cine-CMR are useful for assessment of RV wall motion abnormalities (regional RV akinesia or dyskinesia or dyssynchronous RV contraction) in addition to increased RV volumes and reduced RV EF, which are the CMR diagnostic criteria included in the last 2010 Task Force Criteria (see Fig. 1).[53] Axial and short-axis LGE images are useful for assessment of RV and LV LGE. LV LGE (present in up to 25% of patients with ARVC), instead, has diagnostic value. LGE has mostly a subepicardial/midwall distribution involving especially the posterolateral wall and may be the only sign of LV involvement (Fig. 8). On the basis of LGE, the classification of ARVC has been revised to include the *traditional RV form*, morpho-functional RV abnormalities with or without RV LGE; *LV-dominant form*, LV LGE; *biventricular form*, RV involvement with LV LGE, without LV decreased systolic function; and finally the *end-stage form*, biventricular involvement characterized by both morpho-functional abnormalities with biventricular heart failure and tissue characterization abnormalities of both ventricles.[53–55] Currently, no imaging

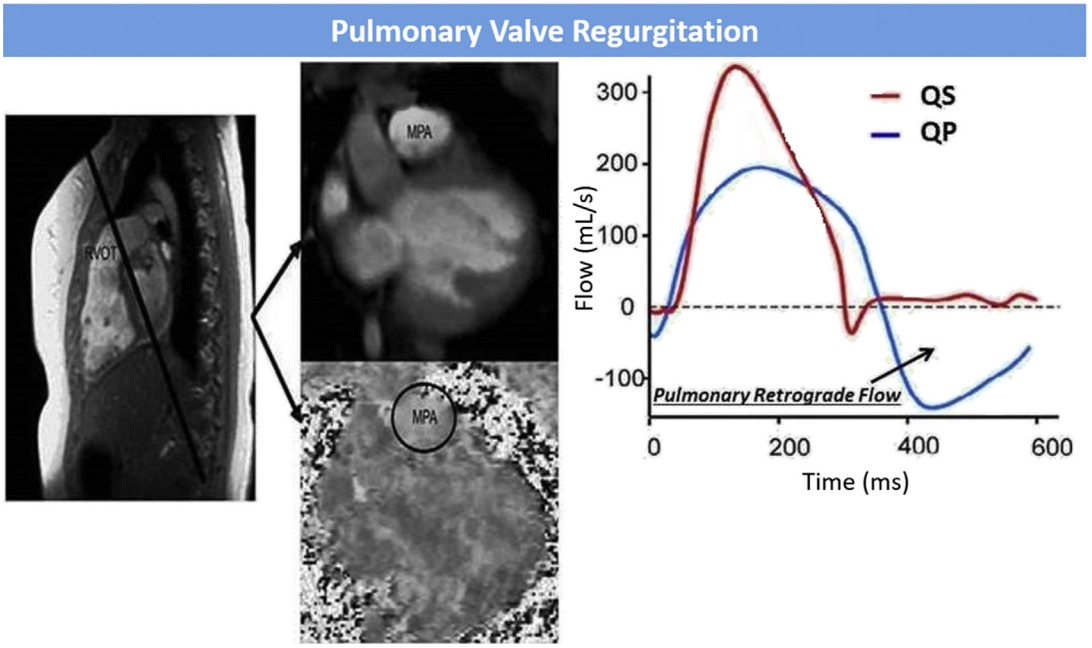

Fig. 6. An example of direct measurement of pulmonary valve regurgitant volume by pulmonary retrograde flow using PC-CMR. PC-CMR, phase contrast cardiac magnetic resonance; QP, pulmonary flow; QS, systemic flow.

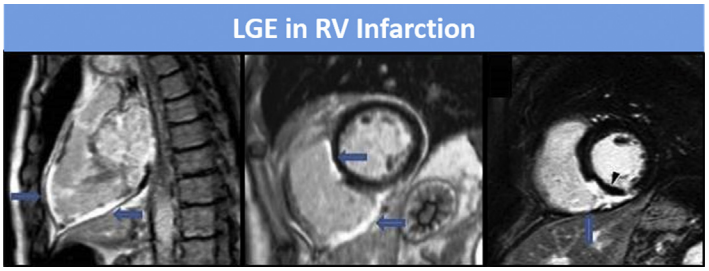

Fig. 7. RV myocardial infarct (*blue arrows*) with involvement of LV inferior wall and microvascular obstruction (*black arrowhead*) demonstrated by LGE-CMR. LGE-CMR, late gadolinium enhancement-cardiac magnetic resonance; LV, left ventricle; RV, right ventricle.

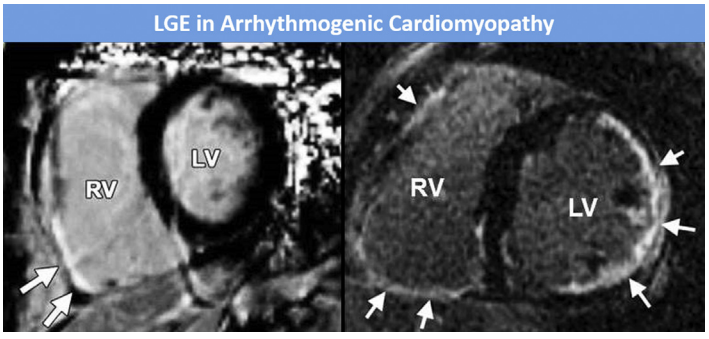

Fig. 8. Examples of LGE in arrhythmogenic cardiomyopathy involving RV and LV (*white arrows*). LGE, late gadolinium enhancement; LV, left ventricle; RV, right ventricle.

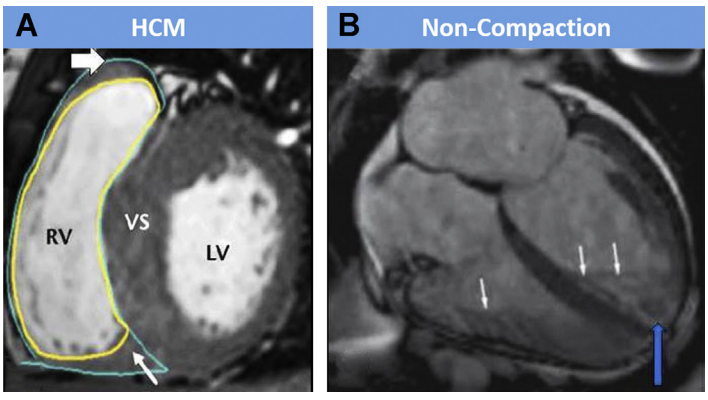

Fig. 9. Short axis showing increased wall thickness in the superior segment and inferior segment (*white arrows*) of the RV wall in hypertrophic cardiomyopathy (*A*) and horizontal long axis showing marked trabeculations in both the LV and RV and an LV thrombus (*blue arrow*) in noncompaction cardiomyopathy (*B*). HCM, hypertrophic cardiomyopathy; LV, left ventricle; RV, right ventricle; VS, ventricular septum.

modality alone (including CMR) can diagnose ARVC.[53] However, CMR evidence of LV involvement is a strong independent predictor of cardiac events in patients with a definite, borderline or possible ARVC diagnosis[54,55] (see **Table 5**).

Other Nonischemic Cardiomyopathies

The RV may also be affected in other nonischemic cardiomyopathies, in which CMR allows early detection of RV involvement[1,2] (**Fig. 9**, see **Table 5**).

SUMMARY

CMR allows accurate and reproducible multiplanar anatomic and functional assessment of the RV, tissue characterization, and blood flow evaluation of the right heart and pulmonary circulation. It also adds precision to evaluation valvular heart disease and shunt severity.

CMR has shown increasing clinical utility in diagnosis, risk stratification, prognosis, and therapeutic management in disorders of the right heart and pulmonary circulation.

CLINICS CARE POINTS

- CMR is the gold standard modality for noninvasive RV imaging.
- CMR is useful in diagnosis, risk stratification, prognosis and therapeutic management in disorders of the right heart and pulmonary circulation.
- Limitations of CMR may include low availability, high cost, claustrophobia, safety in patients with ferromagnetic implants and use of gadolinium in patients with severe chronic renal failure.

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