Right ventricular failure

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Rationale

- RV failure is a complex clinical syndrome. Research has disproportionately focused on the failing LV.

- The RV is anatomically and functionally different from the LV and therefore our knowledge of LV pathophysiology cannot be extrapolated to the Right heart.

Contents

1. Anatomical and physiological features
2. Aetiology and pathophysiology of RVF
3. Diagnosis
4. Management

Sources / refs

1. RV Failure: Pathophysiology, Diagnosis and Treatment. Advanced Heart Failure Cardiac failure review 2019;5(3):140-6
2. Anatomy, Function and Dysfunction of the RV JACC State-of-the-art review Vol 73 No. 12 April 2019
3. Contemporary management of acute RVF: a statement from the Heart Failure Association… of the European Society of Cardiology, European Journal of Heart Failure 2016
4. The ICU book P. Marino 2014

Anatomical/physiological features 1/7

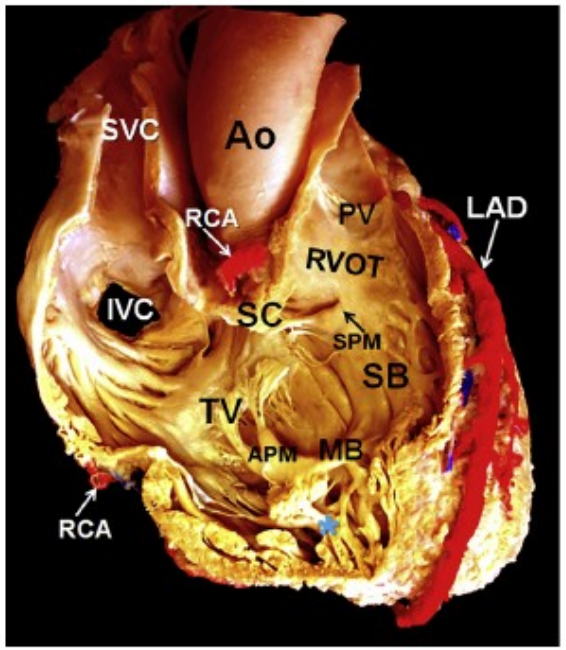
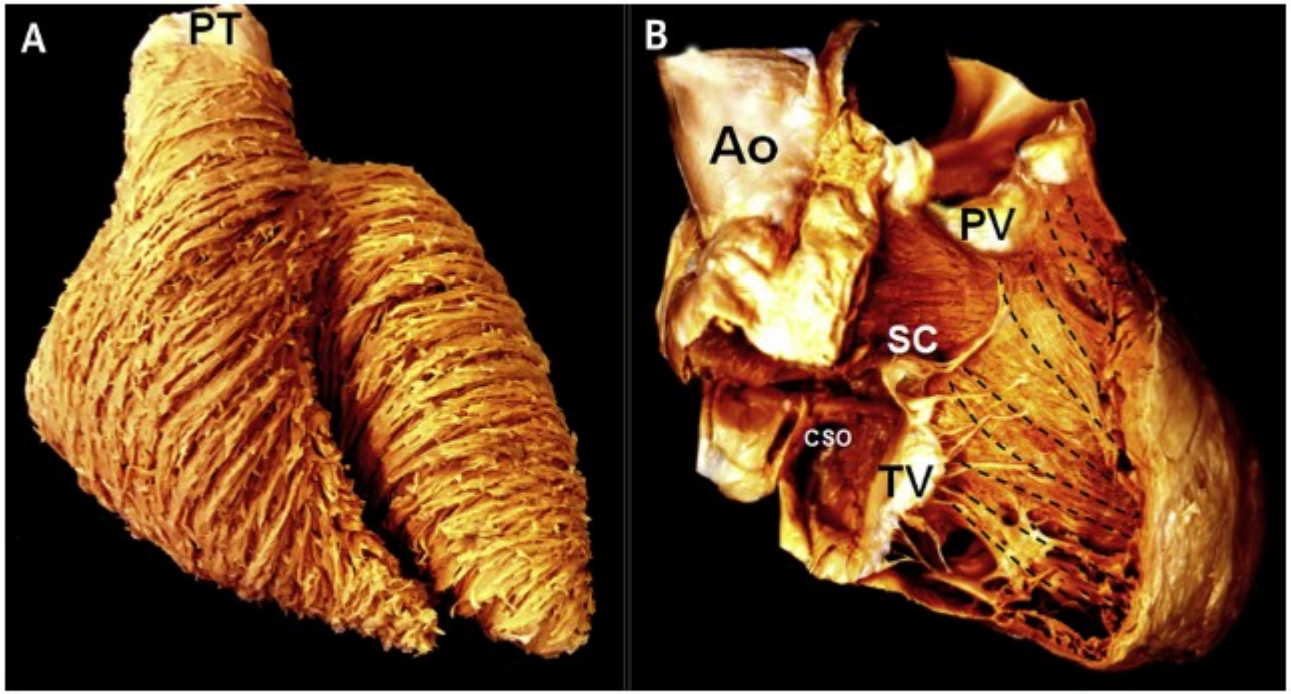


FIGURE 1 Window Dissection of a Heart

Window dissection of a heart prepared by removing the anterior superior wall of the RV, revealing the inlet (TV), trabecular apex (*), and RVOT or infundibulum. Ao = aorta; APM = anterior papillary muscle; IVC = inferior vena cava; LAD = left anterior descending artery; MB = moderator band; PA = pulmonary artery; PV = pulmonary valve; RCA = right coronary artery; RV = right ventricle; RVOT = right ventricular outflow tract; SB = septomarginal or septal band; SC = supraventricular crest; SPM = septal papillary muscle; SVC = superior vena cava; TV = tricuspid valve.

- RV stroke work = 25% LV
- RV thickness = 1/3 LV
- RV volume = 115% LV
- RV contraction : longitudinal shortening (mostly)
  - LV contraction: circumferential
- But both share the septum: 40% of RV contraction depends on septal contraction

FIGURE 2 RV Myoarchitecture



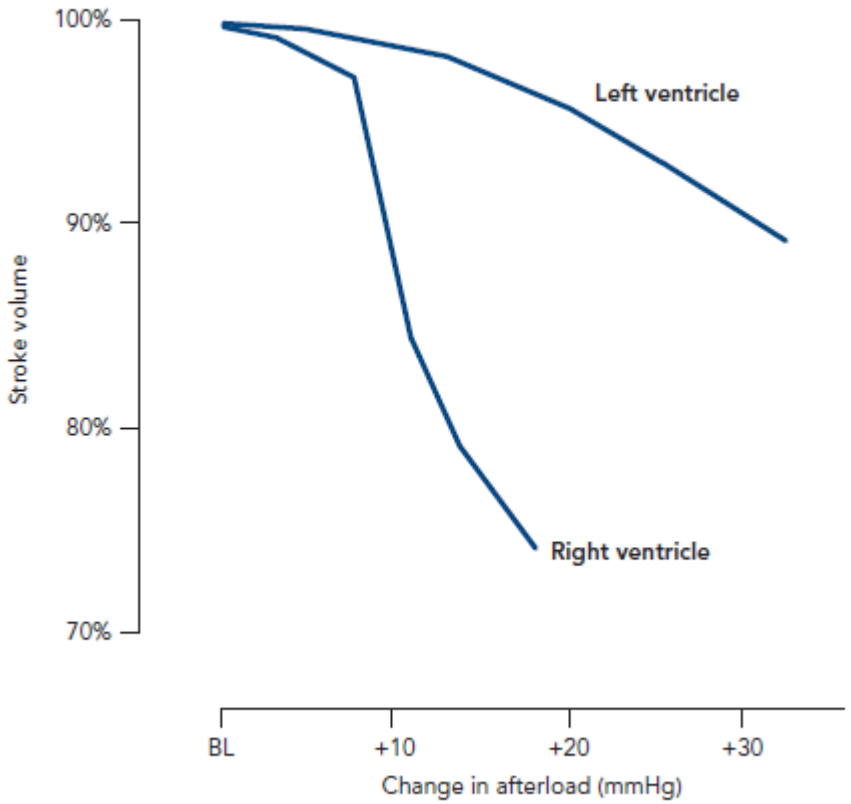
(A) Normal heart viewed from the front shows the circumferential arrangement of superficial RV and middle LV layers of aggregated cardiomyocytes. **(B)** Opened normal RV showing longitudinally arranged subendocardial myocyte aggregates **(black dashed lines).**
CSO = coronary sinus ostium; LV = left ventricle; PT = pulmonary trunk; other abbreviations as in Figure 1.

RV perfusion

- RCA perfuses RV free wall and 1/3 of posterior septum (in RCA dominant, 70-85% population)
- RV perfusion occurs in systole and diastole (LV only diastole) therefore is more vulnerable to
  - RV size increase (high intramural pressure in volume overload) and
  - Hypotension (depends on systole and diastole)

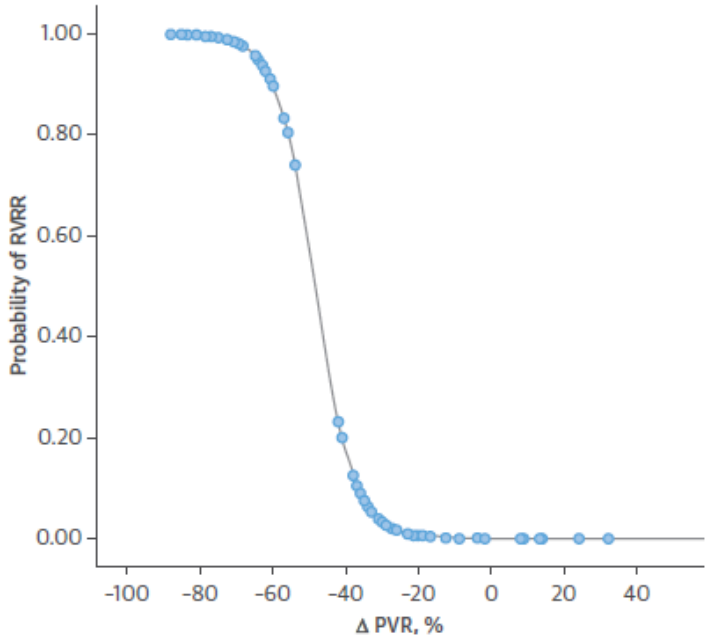
RV relation to afterload

Figure 1: Effect of Increasing Afterload on Stroke Volume of the Right and Left Ventricles



Right ventriclar stroke volume decreases rapidly when afterload is increased, in contrast to left ventricular stroke volume which is maintained against an augmented afterload. BL = baseline.

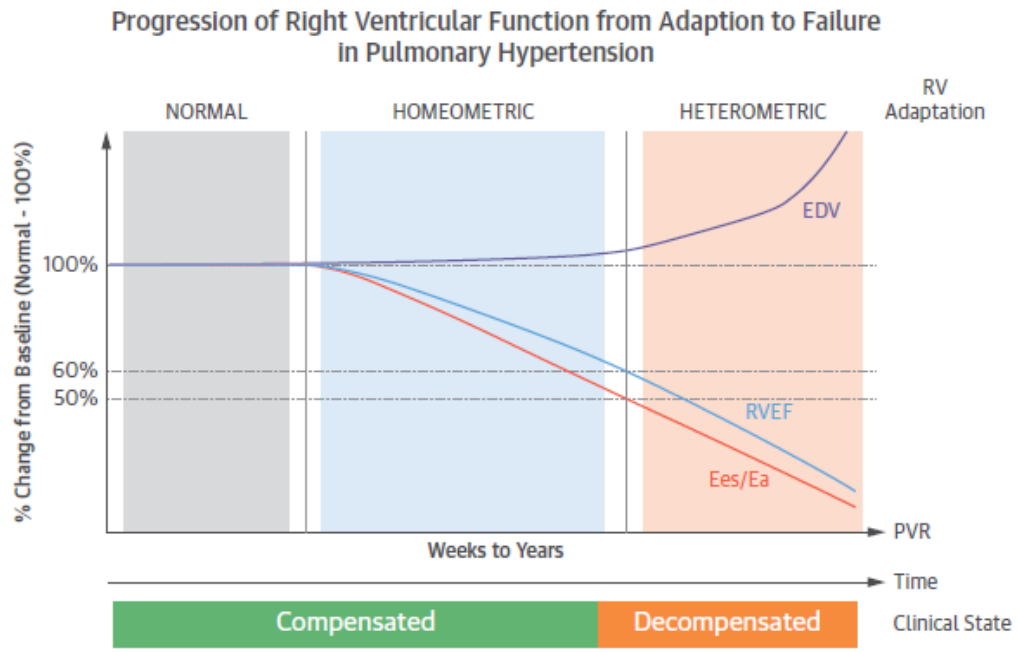
FIGURE 8 Probability of RVRR as a Function of Treatment-Related Decrease in PVR in Pulmonary Arterial Hypertension



Because of the sigmoid shape of the curve, small additional decreases in PVR from −40% to −50% may result in considerable RV improvement. Data from Badagliacca et al. (89) and van de Veerdonk et al. (90). PVR = pulmonary vascular resistance; RVRR = right ventricular reverse remodeling.

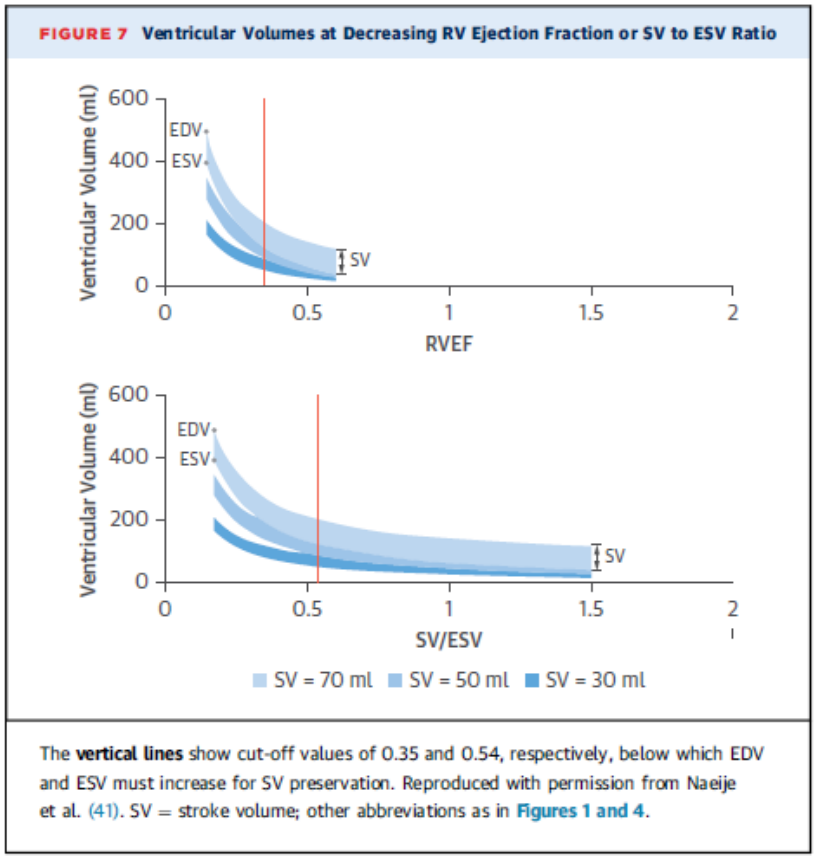
The unconditioned (not used to PA HTN) RV can overcome up to mean PA<40mmHg

FIGURE 6 RV Function Response to a Progressive Increase in PVR in Pulmonary Hypertension



During the adapted "homeometric" phase, contractility increases to maintain the Ees to Ea ratio (Ees/Ea) but does so insufficiently, so that the Ees/Ea progressively declines along with an almost parallel decrease in ejection fraction (EF). Ees/Ea and EF have to decrease, respectively, by >50% and 40% (corresponding to Ees/Ea <0.7 to 0.8 and EF <35%) before heterometric adaptation (Starling's law) is turned on, with rapid progressive increase in EDV and poor prognosis. PVR = pulmonary vascular resistance; other abbreviations as in Figures 1 and 4.

RV dependence on AV synchrony



1. The failing RV (PA HTN) has very limited contractile reserve
   - Cannot increase its SV by increasing contractility in the face of high afterload
2. It is therefore very dependent on regular HR.
   - Diastolic filling depends on atrial contraction + AV synchrony

Ventricular interdependence

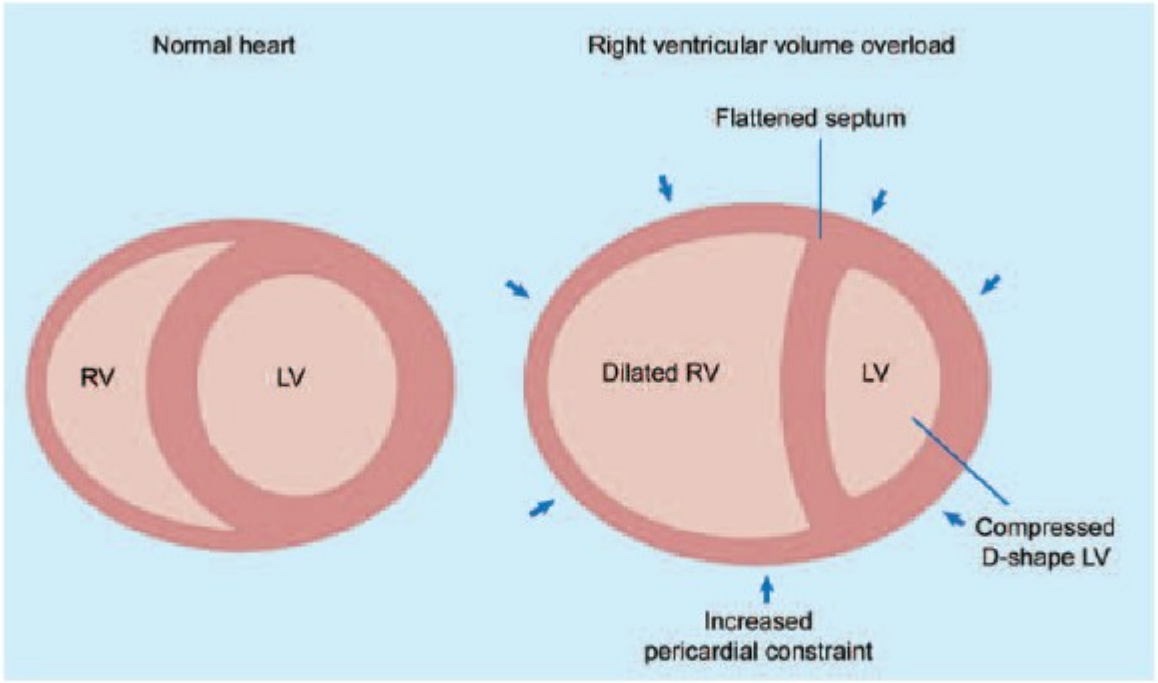


Figure 2 Ventricular interdependence in right ventricular failure. Dilatation of the right ventricle shifts the interventricular septum toward the left, changing left ventricular geometry. Acute right ventricular distension may also lead to an increase in pericardial constraint (arrows). These changes may contribute to low cardiac output state by decreasing left ventricular distensibility, preload, and ventricular elastance. Reprinted with permission from Haddad F, Doyle R, Murphy DJ, Hunt SA. Right ventricular function in cardiovascular disease, part II: pathophysiology, clinical importance, and management of right ventricular failure. *Circulation* 2008;**117**:1717–1731.

Aetiology pathophysiology 1/5

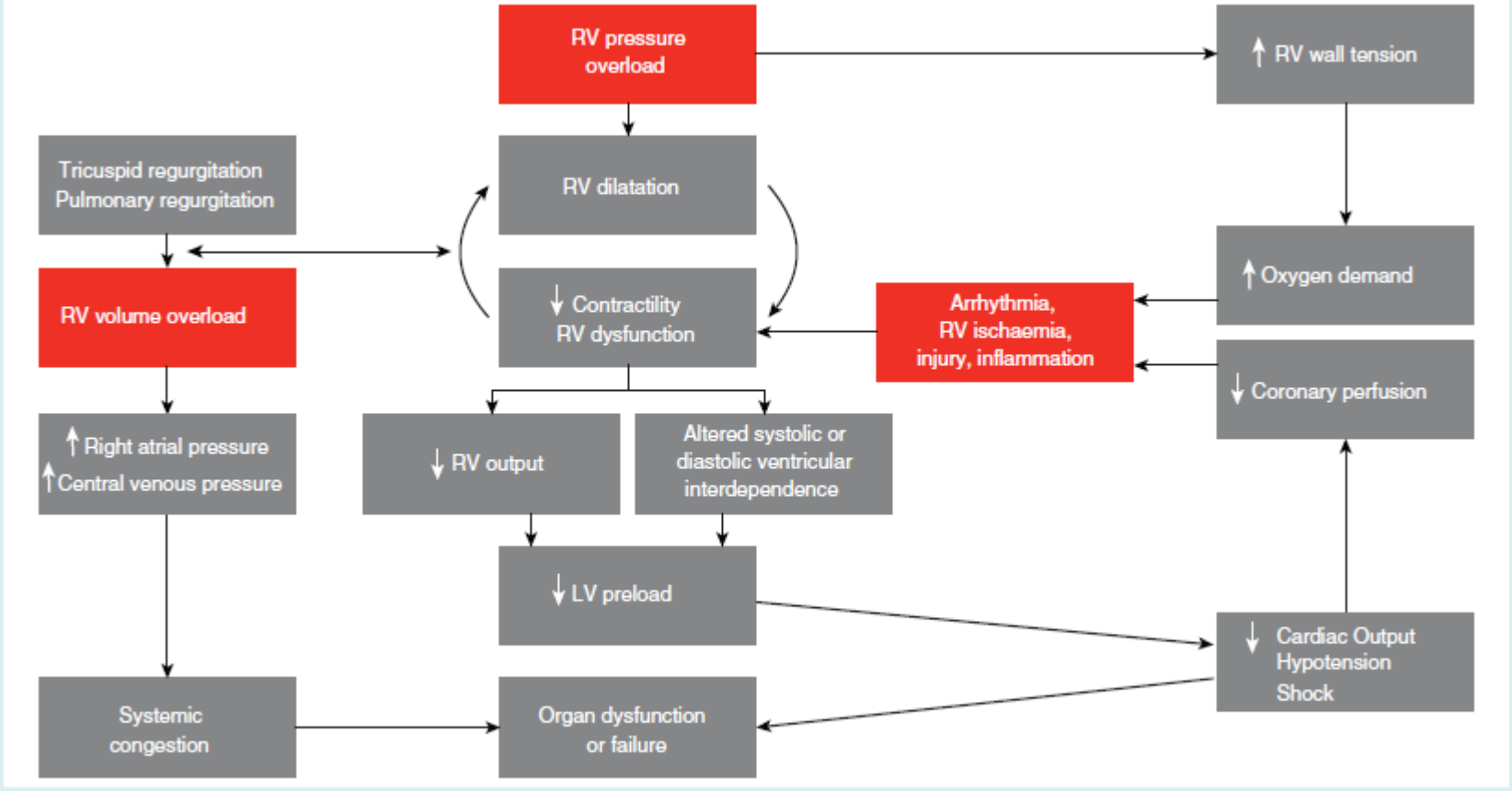
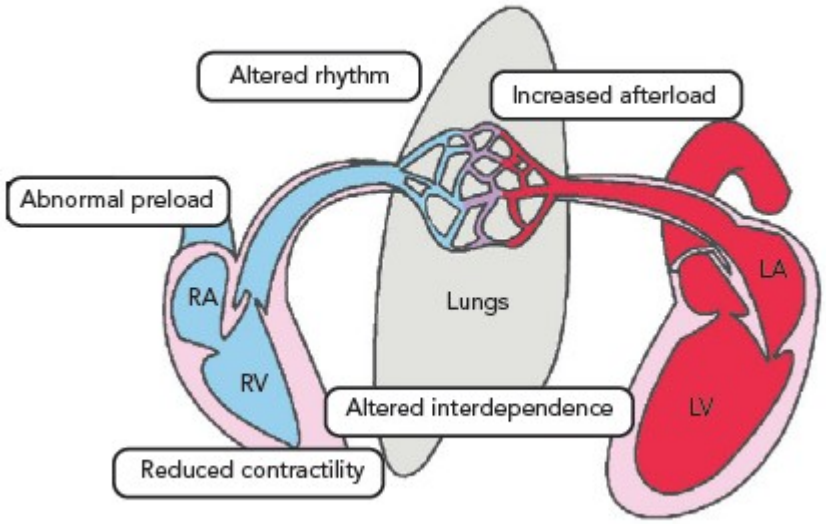


Figure 1 Pathophysiology of acute right ventricular failure. LV, left ventricular; RV, right ventricular.

Pathophysiologic classification

Figure 2: Mechanisms of Right Ventricular Dysfunction



LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle.

Table 1: Mechanisms and Causes of Right Ventricular Failure

Mechanism	Cause
Increased afterload	LV backward failure (pulmonary hypertension associated with left-sided heart disease) Pulmonary embolism, chronic thromboembolic pulmonary hypertension Pulmonary artery hypertension (Exacerbated) chronic pulmonary disease Acute lung injury/acute respiratory distress syndrome Sleep-related breathing disorders, obesity-hypoventilation syndrome Mechanical ventilation (Repaired) congenital heart disease with systemic RV or RV outflow obstruction
Reduced contractility	RV ischaemia/RV infarction RV injury, systemic inflammatory response (SIRS) Myocarditis Cardiomyopathies (e.g. dilated cardiomyopathy or hypertrophic cardiomyopathy) Arrhythmogenic RV cardiomyopathy, Uhl's anomaly
Abnormal preload	Hypo- or hypervolaemia LV forward failure Pericardial tamponade Mechanical ventilation Chronic left-to-right shunt
Altered interdependence	Pericardial tamponade Pericardial disease Septal shift
Altered rhythm	Bradyarrhythmia Tacharrhythmia

LV = left ventricle; RV = right ventricle.

RV specific pathophysiologic classification

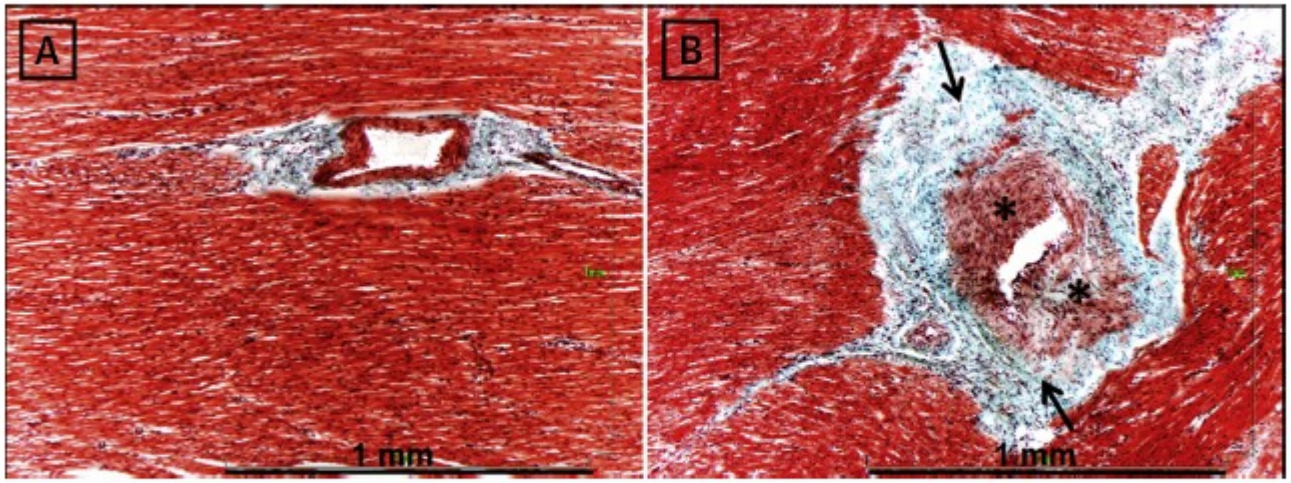
TABLE 1 Etiologies of RV Pressure Overload, Volume Overload, and RV Cardiomyopathy

RV Pressure Overload	RV Volume Overload	RV Cardiomyopathy
Pulmonary hypertension*	Valvular regurgitation	Myocardial infarction
Pulmonary arterial hypertension	Tricuspid	ARVC
Due to left heart disease	Pulmonary	Dilated cardiomyopathy
Due to lung disease and/or hypoxia	Systemic-to-pulmonary shunt	Hypertrophic cardiomyopathy
CTEPH and other pulmonary artery obstructions	Atrial septal defect	Amyloidosis
Unclear and/or multifactorial mechanisms	Partial anomalous pulmonary vein drainage	Myocarditis
Pulmonary valve stenosis	High output states† (i.e., thyrotoxicosis)	Sarcoid
Pulmonary artery stenosis		Transplant
Pulmonary embolism		Post-surgery
		Post-LVAD
		Cardiotoxicity (i.e., chemotherapy)
		Sepsis

*Main groups according to the European Society of Cardiology Classification. †Concomitant left ventricular volume overload.
ARVC = arrhythmogenic right ventricular cardiomyopathy; CETPH = chronic thromboembolic pulmonary hypertension; LVAD = left ventricular assist device; PAPVD = partial anomalous pulmonary vein drainage.

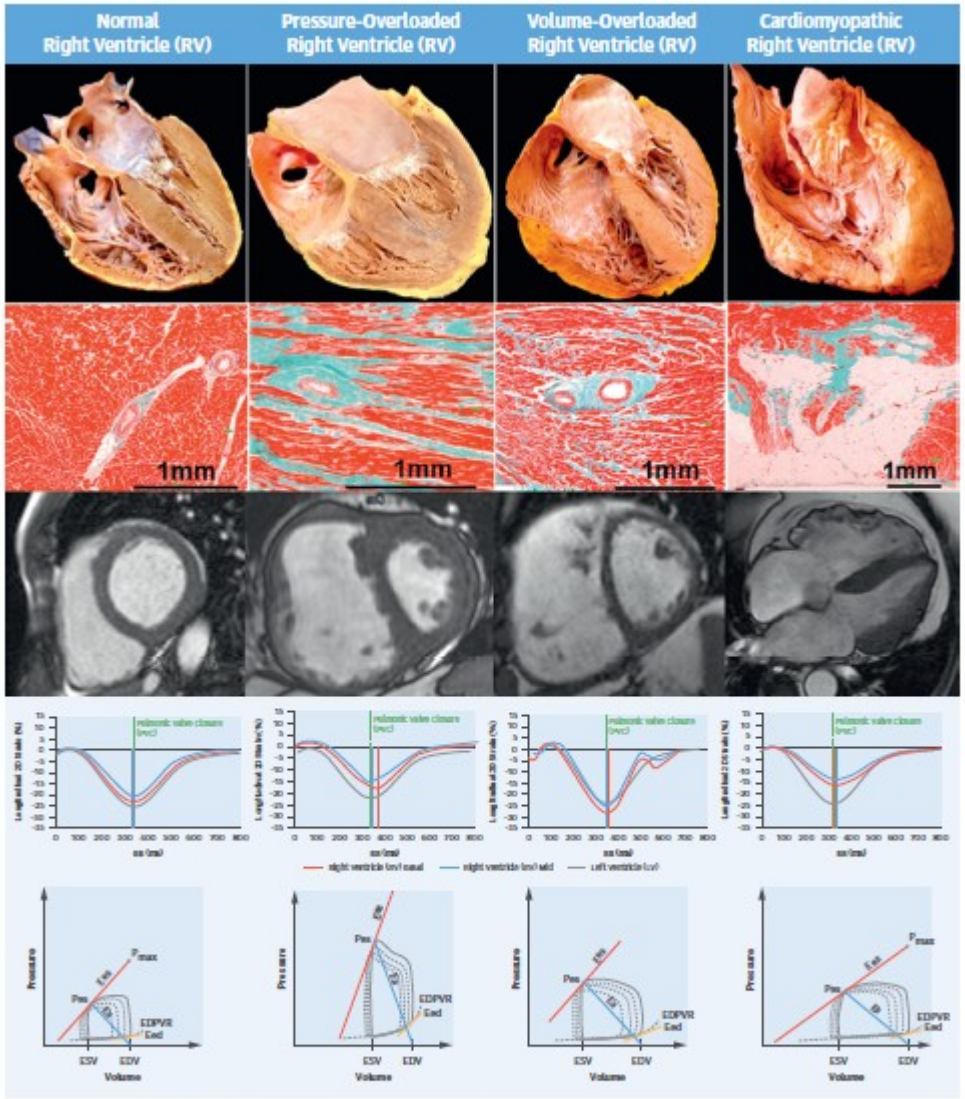
RV myocardium response to PA HTN

FIGURE 5 Histological Sections With Masson's Trichrome Staining of Normal Pig RV Myocardium and After 4 Months of Pulmonary Vein Banding



(A) Normal pig right ventricular (RV) myocardium, and **(B)** after 4 months of pulmonary vein banding. In experimental pulmonary hypertension, there is cardiomyocyte hypertrophy and disarray, arterial medial hypertrophy **(*)**, and lymphocytic infiltration with collagen deposition around blood vessels **(arrows)**.

CENTRAL ILLUSTRATION The Right Ventricle: Anatomy, Function, and Dysfunction



Sanz, J. et al. J Am Coll Cardiol. 2019;73(12):1463-82.

Overview of pathology, histology, magnetic resonance, echocardiography-based strain, and pressure-volume loop findings in the RV in health and disease. The pressure overloaded RV demonstrates hypertrophy and dilatation, systolic septal flattening, extensive fibrosis, reduced myocardial deformation with dyssynchrony and post-systolic shortening, and highest increases in end-systolic (Ees), end-diastolic (Eed), and arterial (Ea) elastances. The volume overloaded RV demonstrates dilatation, diastolic septal flattening, mild fibrosis, near-normal and synchronous myocardial deformation, and preserved coupling. The cardiomyopathic RV (arrhythmogenic cardiomyopathy in the figure) demonstrates RV dilatation and aneurysms, fibrofatty replacement, severely reduced myocardial strain, and decreased Ees. 2D = 2-dimensional; EDPVR = end-diastolic pressure-volume relationship; EDV = end-diastolic volume; ESV = end-systolic volume; LV = left ventricle; Pes = end-systolic pressure; PVC = pulmonic valve closure; RV = right ventricular.

Diagnosis 1/5

Table 2 Clinical signs and biochemical markers of acute right ventricular (RV) failure

Clinical signs	Biochemical markers
Hypoxaemia	Increased lactate levels
Signs of systemic congestion	Elevated natriuretic peptides (BNP or NT-proBNP)
Jugular venous distension, hepatojugular reflux	Elevated cardiac troponin I or T
Peripheral oedema, pericardial effusion, congestive hepato/splenomegaly, ascites, anasarca*	Abnormal liver biochemistry (e.g. elevated transaminases, bilirubin, prolonged prothrombin time)
Signs of right ventricular dysfunction	Abnormal renal function (blood urea nitrogen, creatinine)
Third heart sound, systolic murmur of tricuspid regurgitation, hepatic pulse, signs of concomitant left ventricular dysfunction	D-dimer levels†
Paradoxical pulse	
Signs of low cardiac output state	
Hypotension, tachycardia, cool extremities, central nervous system abnormalities, oliguria	

BNP, brain natriuretic peptide; NT-proBNP, *N*-terminal pro brain natriuretic peptide.
*Particularly in acute decompensation of chronic RV failure.
†D-dimer testing is used in the diagnostic workup of suspected pulmonary embolism.

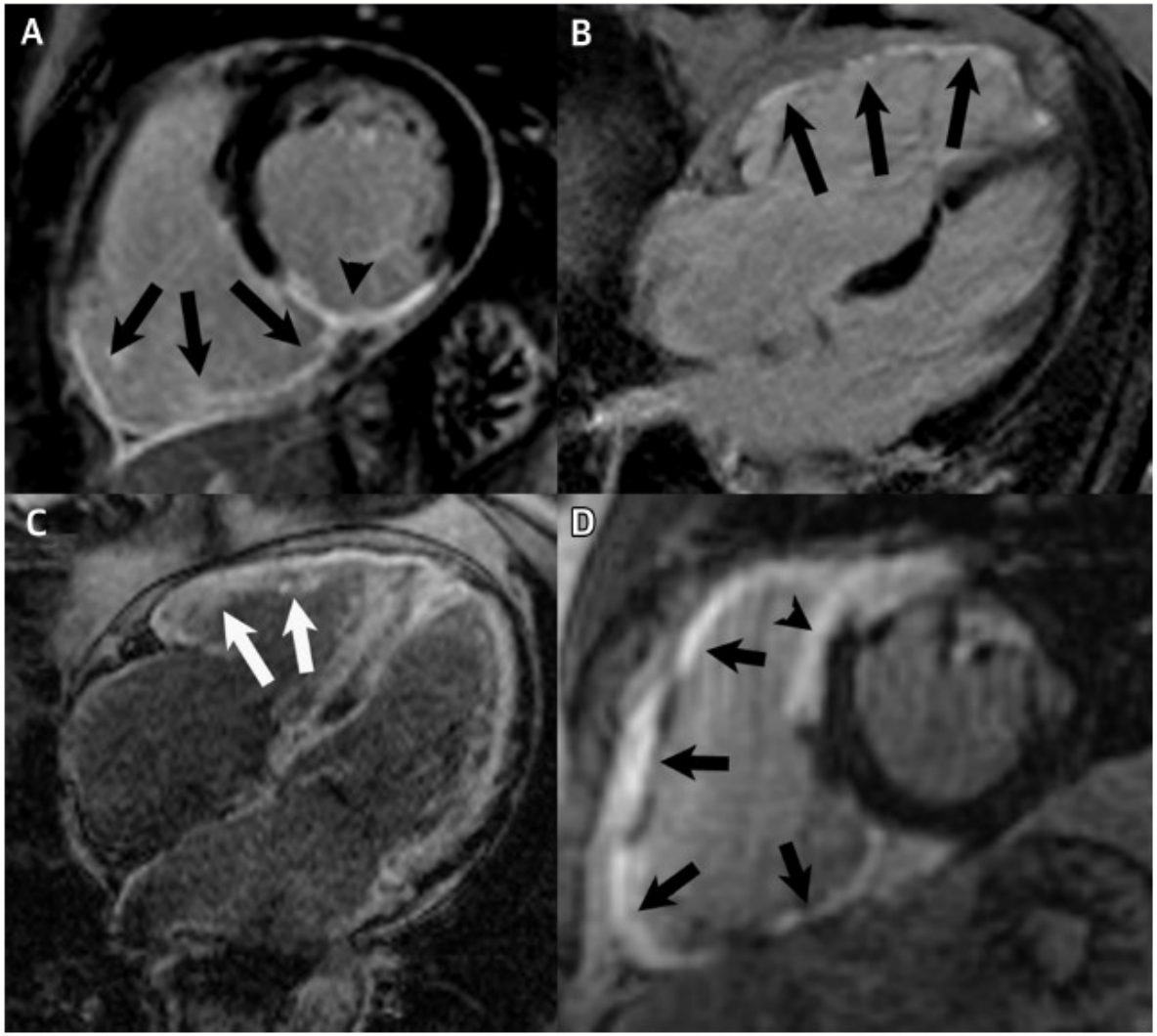
TABLE 2 Summary of Invasive and Noninvasive Modalities for RV Assessment and Their Measured Parameters

Invasive	
Right heart catheterization	
Contrast ventriculography	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, regional wall motion
Standard catheterization	End-diastolic pressure, peak systolic pressure
Thermodilution	Cardiac output, stroke volume
High-fidelity micromanometer	dp/dt
Conductance catheter	End-systolic elastance, arterial elastance, end-diastolic elastance, stiffness constant β, stroke work, preload recruitable stroke work, RV power
Intracardiac echocardiography	Dimensions and function
Noninvasive	
Ultrasound	
M-mode	TAPSE, diameters, wall thickness, right atrial size
2D	Fractional area change, eccentricity index, wall thickness, regional wall motion, right atrial size Speckle tracking: myocardial strain, strain rate, dyssynchrony
3D	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, wall thickness, regional wall motion, right atrial size Speckle tracking: myocardial strain, strain rate, dyssynchrony
Doppler	E, A, deceleration time, isovolumic relaxation time, myocardial performance index, dp/dt, stroke volume Tissue Doppler: E′, A′, E/E′, S′, myocardial performance index, peak isovolumic velocity, isovolumic acceleration, strain, strain rate, dyssynchrony
Contrast	Intraventricular flow patterns, vorticity
Magnetic resonance imaging	
Cine	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, mass, regional wall motion, right atrial size Feature tracking: strain, strain rate, dyssynchrony
Tagging	Strain
Strain encoded imaging (SENC)	Strain
Phase contrast	Stroke volume, cardiac output, myocardial velocity
Contrast first-pass imaging	Myocardial perfusion
T2-weighted imaging	Myocardial edema
Late gadolinium enhancement	Fibrosis/necrosis
T1-mapping	Native T_1, ECV
Computed tomography	
Noncontrast	Myocardial fatty infiltration
Contrast-enhanced*	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, mass, wall thickness, regional wall motion, right atrial size
Nuclear imaging	
First-pass radionuclide angiography	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction
Equilibrium radionuclide angiography	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction
SPECT	
99TC-tracers	End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, perfusion
BMIPP	Fatty acid metabolism
PET	
^{18}F-FDG	Glucose metabolism
^{11}C-palmitate	Fatty acid metabolism
^{18}F-FTHA	Fatty acid metabolism
^{11}C-acetate	Oxygen consumption
$^{15}O_2$-tracers	Oxygen consumption
Cardiopulmonary exercise test	Peak oxygen consumption, minute ventilation, ventilatory efficiency, oxygen pulse

*Retrospective ECG gating.

2D = 2-dimensional; 3D = 3-dimensional; BMIPP = ^{123}I beta-methyl-p-iodophenyl-pentadecanoic acid; ECV = extracellular volume; FDG = fluorodeoxyglucose; FTHA = fluoro-6-thioheptadecanoic acid; PET = positron emission tomography; SPECT = single photon emission computed tomography; TAPSE = tricuspid annular plane systolic excursion.

FIGURE 9 Magnetic Resonance Images of Different Cardiomyopathies



(A) Inferior myocardial infarction **(arrowhead)** with involvement of the right ventricular (RV) inferior wall as demonstrated by late gadolinium enhancement **(arrows)**. **(B)** RV free wall fibrosis **(arrows)** in a patient with arrhythmogenic cardiomyopathy. **(C)** RV enhancement **(white arrows)** secondary to amyloid infiltration. **(D)** Cardiac sarcoidosis with extensive late gadolinium enhancement in the septum **(arrowhead)** and RV free wall **(arrows)**.

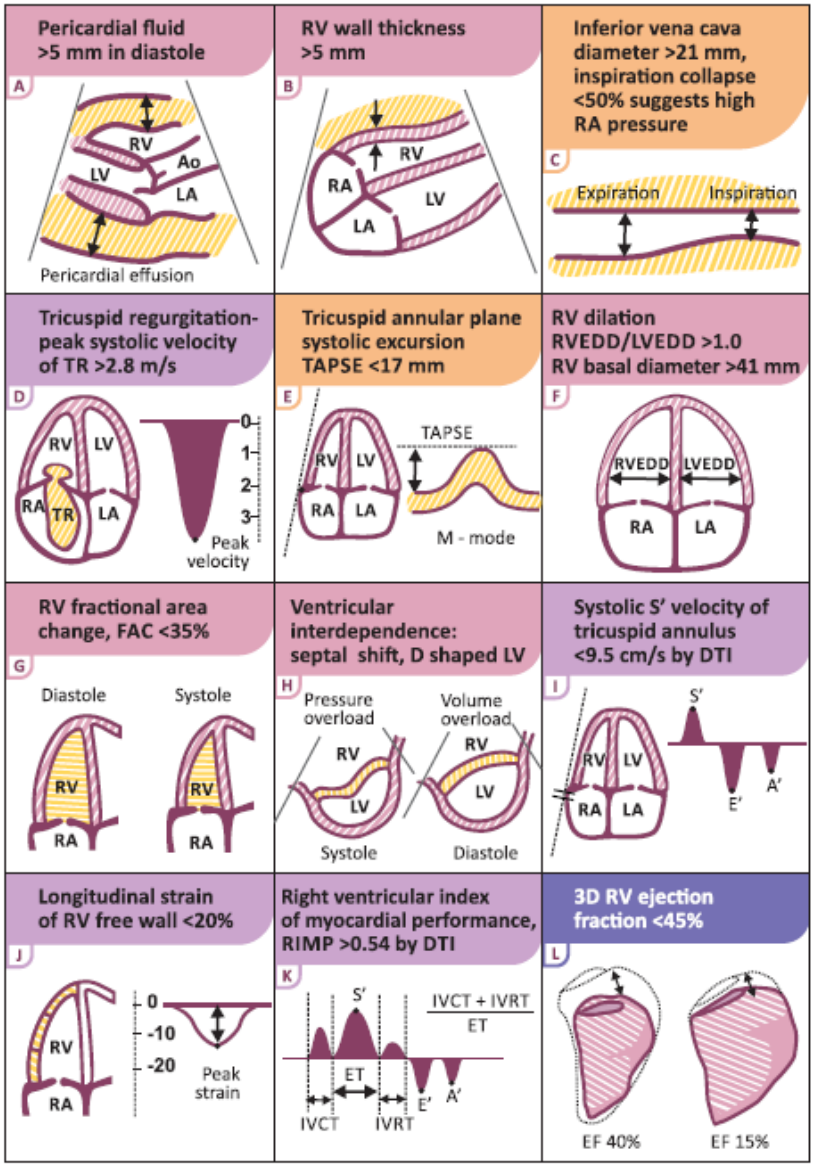


Figure 3 Graphic representation of echocardiographic parameters in the assessment of right ventricular failure. Ao, aorta; DTI, Doppler tissue imaging; EF, ejection fraction; ET, ejection time; FAC, fractional area change; IVC, inferior vena cava; IVCT, isovolumic contraction time; IVRT, isovolumic relaxation time; LA, left atrium; LV, left ventricle; LVEDD, left ventricular end-diastolic diameter; RA, right atrium; RIMP, right ventricular index of myocardial performance; RV, right ventricle/ventricular; RVEDD, right ventricular end-diastolic diameter; TAPSE, tricuspid annular plane systolic excursion; TR, tricuspid regurgitation.

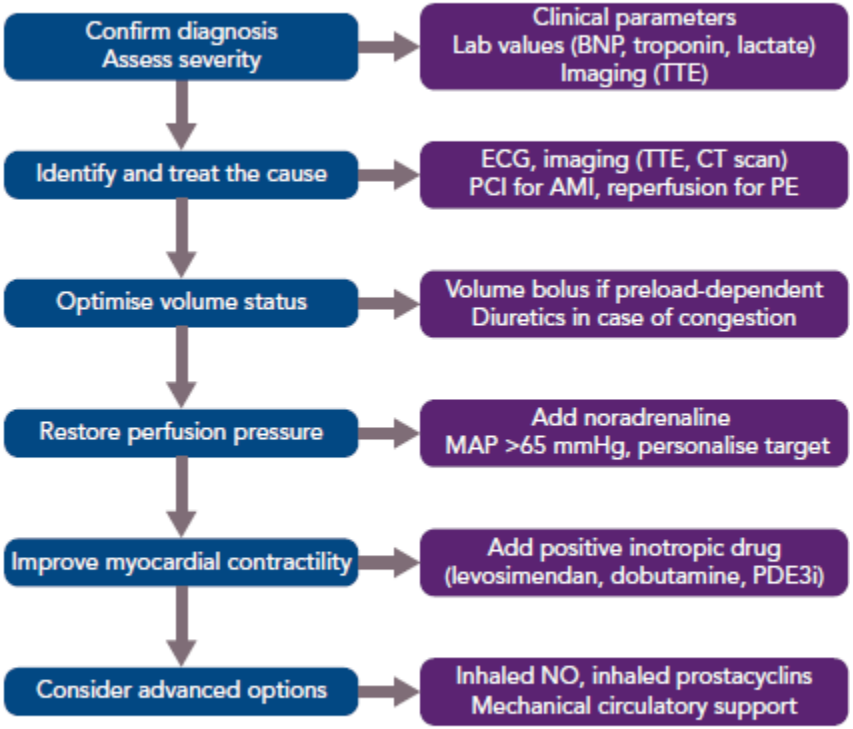
Table 3 Echocardiographic findings in specific clinical settings

Acute pulmonary embolism (Supplementary material online, *Cases S4, S5*)	Increased RV/LV end-diastolic diameter ratio
	Regional hypokinesia (McConnell's sign*)
	Systole-diastolic septal shift (D-shaped left ventricle), paradoxical septal motion
	Peak systolic velocity of TR jet 2.8–3.5 m/s
	Thrombi in proximal pulmonary arteries
Chronic pulmonary hypertension (acute decompensation)	RV hypertrophy
	RV dilation, spherical shape present in advanced stages
	Systolic/diastolic septal shift, paradoxical septal motion
	Peak systolic velocity of TR jet often >3.5 m/s
	RA enlargement (Supplementary material online, *Cases S1, S2*)
Cardiac tamponade (Supplementary material online, *Case S8*)	Moderate to severe diffuse pericardial effusion (can be compartmentalized after surgery)
	RA systolic and RV diastolic collapse
	LA and LV collapse in case of localized post-surgical tamponade
	Reciprocal respiratory changes (>25%) in RV and LV filling registered by pulsed Doppler method at tricuspid and mitral valves
	Normal or slightly elevated PA pressure
RV myocardial infarction (Supplementary material online, *Cases S6, S7*)	RV dilation
	Global and regional hypokinesia
	Abnormal septal motion
	Reduced TAPSE
	Reduced S′ velocity
	Congested IVC despite normal or low systolic RV pressure
	Signs of elevated RA and diastolic RV pressure
Cardiomyopathies	DCMP: symmetric pattern of LV and RV dilation and reduced systolic function; pulmonary artery pressures are elevated in variable degrees
	ARVC: RV dilation and systolic dysfunction, small free wall aneurysms, prominent trabeculation of the right ventricle
	Chagas disease: biventricular apical aneurysms
	Amyloidosis, restrictive infiltrative cardiomyopathy: increased RV wall thickness, biatrial dilation
	Takotsubo: global or focal RV apical involvement in 50% of patients
RV failure after LVAD implantation	Visually defined significant systolic RV dysfunction
	RV dilation
	Pronounced septal shift with collapse of LA and LV
	Moderate to severe TR

ARVC, arrhythmogenic right ventricular cardiomyopathy; DCMP, dilated cardiomyopathy; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; PA, pulmonary artery; RA, right atrial; RV, right ventricular; RVEF, right ventricular ejection fraction; TAPSE, tricuspid annular plane systolic excursion; TR, tricuspid regurgitation.
*Akinetic mid RV free wall segment with spared apical contractility.

Management 1/4

Figure 3: Algorithm for the Treatment of Acute Right Ventricular Failure



AMI = acute MI; BNP = B-type natriuretic peptide; MAP mean arterial pressure; NO = nitric oxide; PCI = percutaneous coronary intervention; PDE3i = phosphodiesterase-3 inhibitor; PE = pulmonary embolism; TTE = transthoracic echocardiography. Adapted from Harjola et al. 2016.[33]

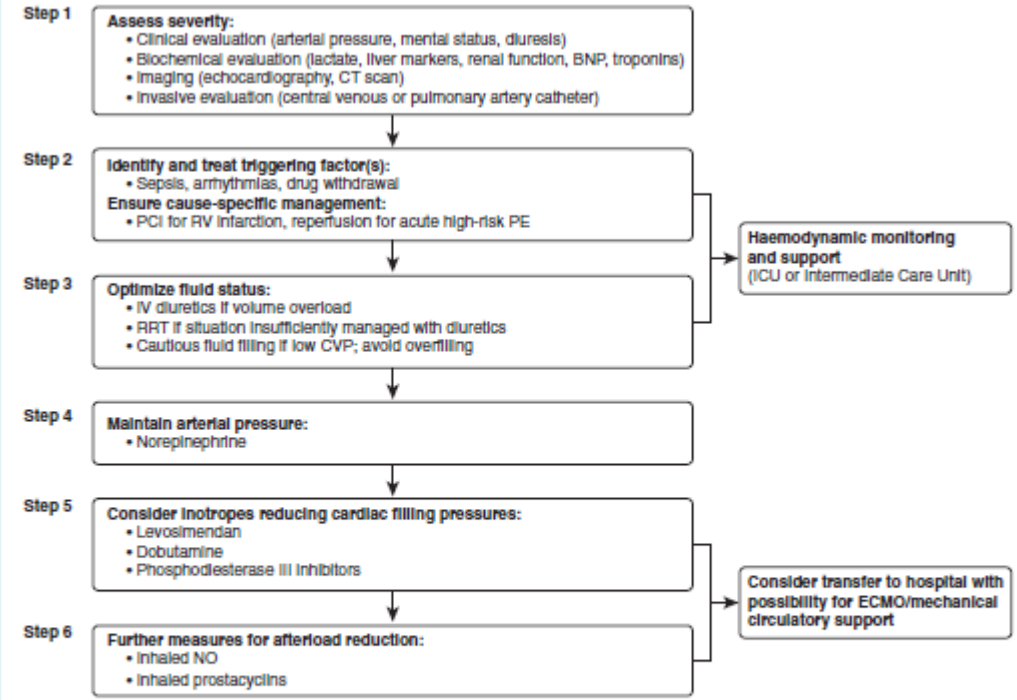


Figure 4 Comprehensive care of patients affected by right ventricular failure. Modified from Sztrymf B *et al.* Acute right heart failure in pulmonary hypertension patients. In Gaine S, Naeije R, Peacock A, eds. *The Right Heart*. Springer Verlag, London, 2013, pages 261–275. BNP, B-type natriuretic peptide; CT, computed tomography; CVP, central venous pressure; ECMO, extracorporeal membrane oxygenation; ICU, intensive care unit; IV, intravenous; NO, nitric oxide; PCI, percutaneous coronary intervention; PE, pulmonary embolism; RRT, renal replacement therapy; RV, right ventricular.

Table 4 Overview of acute right ventricular (RV) failure treatment

Strategy	Properties and use	Caveats
Volume optimization		
Volume loading, saline or ringer lactate, >200 mL/15–30 min[29]	Consider in patients with decompensated RV failure, normal central venous pressure, low arterial pressure	Volume loading can overdistend the ventricles, worsen ventricular interdependence, and reduce cardiac output
Diuretics		
In patients not receiving oral diuretics the initial dose should be 20–40 mg iv; for those on chronic diuretic therapy, initial dose of furosemide should be at least equivalent to the oral dose	Intravenous loop diuretics are recommended for all patients admitted with signs/symptoms of fluid overload to improve symptoms Can be given either as intermittent boli or continuous infusion Combination of loop-diuretic with either thiazide-type diuretic or spironolactone may be considered in patients with resistant oedema or insufficient symptomatic response	May cause worsening renal function and hypokalaemia
Vasopressors and inotropes		
Noradrenaline, 0.2–1.0 μg/kg.min[30]	Increases RV inotropy, systemic blood pressure, promotes positive ventricular interactions, restores coronary perfusion gradient	Excessive vasoconstriction may worsen tissue perfusion
Dobutamine, 2–20 μg/kg.min[30]	Increases RV inotropy, lowers filling pressures	May aggravate arterial hypotension if used alone, without a vasopressor, especially if left heart failure present May trigger or aggravate arrhythmias
Levosimendan, 0.1–0.2 μg/kg.min (6–12 μg/kg bolus over 10 min is optional and not recommended if SBP <90 mmHg). Infusion can be decreased to 0.05 μg/kg.min or increased to 0.2 μg/kg.min)[30]	Combines RV inotropy and pulmonary vasodilation; favourably affects right ventricular–arterial uncoupling	May aggravate arterial hypotension May trigger or aggravate arrhythmias
Mechanical circulatory support		
ECMO/ECLS	Short-term support, rapid; oxygenator can be added	Complications with use over longer periods (>5–10 days)
Percutaneous catheter mounted micro-axial pumps		Limited pump capacity; ECLS preferred in severe cardiogenic shock or where high pump flow required
Paracorporeal RVADs	Appropriate for longer term use (e.g. weeks or months); can be combined with oxygenators when pulmonary support also needed	

ECLS, extracorporeal life support; ECMO, extracorporeal membrane oxygenation; RVAD, right ventricular assist device; SBP, systolic blood pressure.

Summative management algorithm

1. Restore HR.
   - Use sequential A-V pacing
   - Avoid ventricular pacing,
   - Promptly control SVTs (amiodarone, cardioversion etc.)
2. Optimise volume status
   - Fluid boluses (if PAWP<15mmHg) until PAWP=20mmHg or CVP=20mmHg
   - Diuretics frusemide (loop) iv +/- metolazone (thiazide) +/- RRT
3. Restore systemic BP (coronary perfusion)
   - Use Norad and/or vasopressin (no effect on PVR) aiming at MAP >65mmHg or higher if CVP is high
   - Renal: MAP-CVP>65mmHg,
   - Brain: MAP-CVP>60-70mmHg,
   - Hepato-spachnic: MAP-CVP>50mmHg
4. Contractility
   - When CVP>15mmHg or PAWP>15mmHg start inodilators: Levosimendan, milrinone, dobutamine
   - Avoid adrenaline
5. The role of pulmonary vasodilators is highly controversial

RV failure and cardiac surgery

1. ‘Cardiac surgery should be planned anticipating RV failure and RV function management should focus on prevention’.
2. High risk patients:
   - PA HTN,
   - RV dysfunction,
   - Severe LV impairment,
   - Long CPB time
3. Avoid liberal transfusion strategies
   - use caution in coagulopathy and products
4. Maintain AV synchrony

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