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Management of Acute Right Ventricular Failure

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Abstract

Purpose of Review Acute right ventricular failure (RVF) is a frequent condition associated with high morbidity and mortality. This review aims to provide a current overview of the pathophysiology, presentation, and comprehensive management of acute RVF.

Recent Findings Acute RVF is a common disease with a pathophysiology that is not completely understood. There is renewed interest in the right ventricle (RV). Some advances have been principally made in chronic right ventricular failure (e.g., pulmonary hypertension). Due to a lack of precise definition and diagnostic tools, acute RVF is poorly studied. Few advances have been made in this field.

Summary Acute RVF is a complex, frequent, and life-threatening condition with several etiologies. Transthoracic echocardiography (TTE) is the key diagnostic tool in search of the etiology. Management includes transfer to an expert center and admission to the intensive care unit (ICU) in most severe cases, etiological treatment, and general measures for RVF.

Keywords Heart failure · Right ventricular failure · Right ventricular dysfunction · Echocardiography · Pulmonary vasodilator · Mechanical circulatory support

Introduction

Acute right ventricular failure (RVF) is a frequent and life-threatening condition defined as a clinical syndrome related to structural and/or functional impairment of the right ventricle (RV) decreasing its capacity of blood ejection through the pulmonary circulation [1]. Although historically less studied than the left ventricle (LV), research and clinical interest in the RV have been growing in the past decades. The role of the RV is to keep the right atrium pressure as low as possible by ejecting blood through the pulmonary system which is characterized by low resistances. However, RVF is a frequent pathology associated with a poor prognosis [1, 2] with the same incidence as left ventricular failure (LVF) [1]. Etiologies of RVF are various including myocardial infarction (MI), acute respiratory distress syndrome (ARDS), pulmonary embolism (PE), myocarditis, pericarditis, arrhythmias, and pulmonary hypertension (PH) [3]. The dramatic increase in RV afterload that may occur after PE, tension pneumothorax, or ARDS leads to a dilation of the RV and increased right heart pressures, also known as acute cor pulmonale [4–7].

During the past few years, there has been a growing interest in the RV. It is now clearly established that the RV plays an essential role in the cardiovascular system and its failure may negatively impact the prognosis [8]. Transthoracic echocardiography (TTE) is the key diagnostic tool in search of the etiology. After some physiological reminders on the RV, this review focuses on the pathophysiological basis, the diagnosis, and the management of acute RVF according to the current state of knowledge on the subject.

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Physiology of RV

Definition

Acute RVF is defined as a clinical syndrome related to structural and/or functional impairment of the RV with systemic congestion resulting from impaired RV filling and/or reduced flow output [1, 9]. A clear definition of RVF is lacking but frequently includes RV dilation (e.g., RV/LF ratio > 0.6 on echocardiography) and paradoxical septal motion [1, 2, 9]. Chronic RVF is a consequence of increasing pressure in the RV caused by PH, most frequently observed in pulmonary disease or chronic heart failure (CHF) [10].

Anatomy and Physiology

The right ventricle is a thin muscular structure (its muscle mass is six times less than that of LV) wrapped around the LV. It is triangular in shape, with the base formed by the tricuspid annulus at the top of the tricuspid valve which has three anatomic faces: septal (contacting the interventricular septum), anterior, and posterior. These proceed into the tendinous cords followed by the papillary muscles. The apex, including the sinus, is trabeculated and the outlet or infundibulum includes the conus, which is a tubular muscular structure supporting the pulmonary valve leaflets [11–13].

The right ventricle connects the systemic circulation and the pulmonary circulation at low resistance and high compliance [13]. Its role is to keep right atrium pressures as low as possible by ejecting blood continuously into the pulmonary arterial system. This continuous blood ejection is made possible by the specificities of the pulmonary vascular bed, characterized by low pressures and low resistances. Histologically, the RV is formed by trabecular muscles [14]. During its contraction, the RV performs a complex peristaltic motion around the LV from the conus to the infundibulum. The right ventricle shares common muscle fibers with LV [11], explaining the phenomenon of ventricular coupling due to the participation of the LV to the RV contraction [15–17].

The vascularization of the RV is complex [13]. Most of the vascularization of the RV is based on the right coronary artery (from the base of RV to the apex) explaining why its occlusion is followed by an extensive ischemia of the RV. [18]

The right ventricular function depends on several factors summarized in Fig. 1.

Myocardial Contractility

Myocardial contractility is defined as the inherent ability of cardiomyocytes to contract independently of loading conditions and corresponds to the force of contraction per unit of time developed by these cells. Although this concept is particularly interesting from a physiological point of view, its measurement is not possible under experimental conditions [18].

Preload Conditions of RV

Preload conditions correspond to RV end-diastolic pressure (or the level of maximal stretch of myocardial fibers before isovolemic contraction) [13]. Right ventricular preload conditions are influenced [14] by venous return, the volume of the venous system, compliance of the RV, heart rate, LV filling pressures, and intrapericardial pressures.

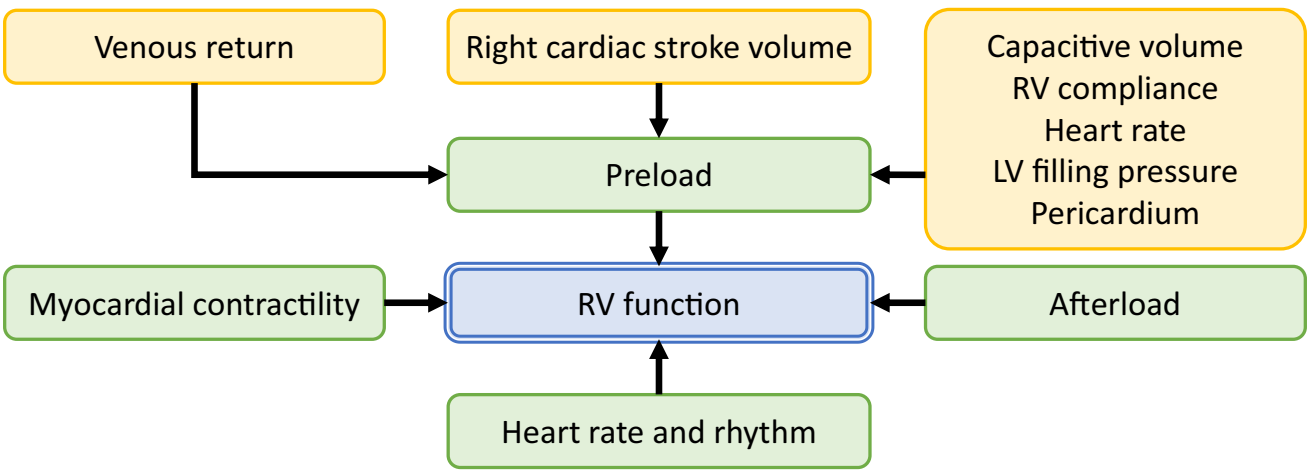

Fig. 1 Determinants of right ventricular function. RV right ventricle (or right ventricular), LV left ventricle (or left ventricular)

Afterload Conditions of RV

Defined as the resistive power opposing myocardial fibers during contraction, afterload is the determining factor of myocardial oxygen consumption. Therefore, increased RV afterload induces an increase in RV oxygen requirements [19]. Because the RV myocardium is thin (high compliance), increased afterload conditions will result in RV dilation without an increase in diastolic pressures.

Heart Rate

Heart rate is an important determinant of cardiac output (CO). During tachycardia, RV filling time is reduced (while the systolic ejection time is unchanged) inducing a reduction in the systolic ejection volume.

Ventricular Geometry

The change in LV geometry (anatomic changes, arrhythmias, and conduction disturbances) has direct consequences on RV performance and systolic ejection volume.

Ventricular Coupling

The right and left ventricles are anatomically arranged in series, enclosed in an inextensible pericardial sac, making them dependent on each other [20]. In case of an increased volume of the RV (PE for example), the interventricular septum is displaced toward the LV during diastole, resulting in an increase in left heart pressures and a decrease in systolic ejection volume (Bernheim reverse effect) [18, 20–23].

Pathophysiology of RVF

The pathophysiology of acute RVF summarized in Fig. 2 is complex and incompletely understood and involves several factors, namely:

- Reduced RV contractility (RV infarction, right heart cardiomyopathy, post-operative RV failure)
- Volume overload (tricuspid or pulmonary insufficiency)
- Pressure overload (PH, PE, left heart cardiomyopathy, ARDS, cardiac tamponade, pneumothorax)

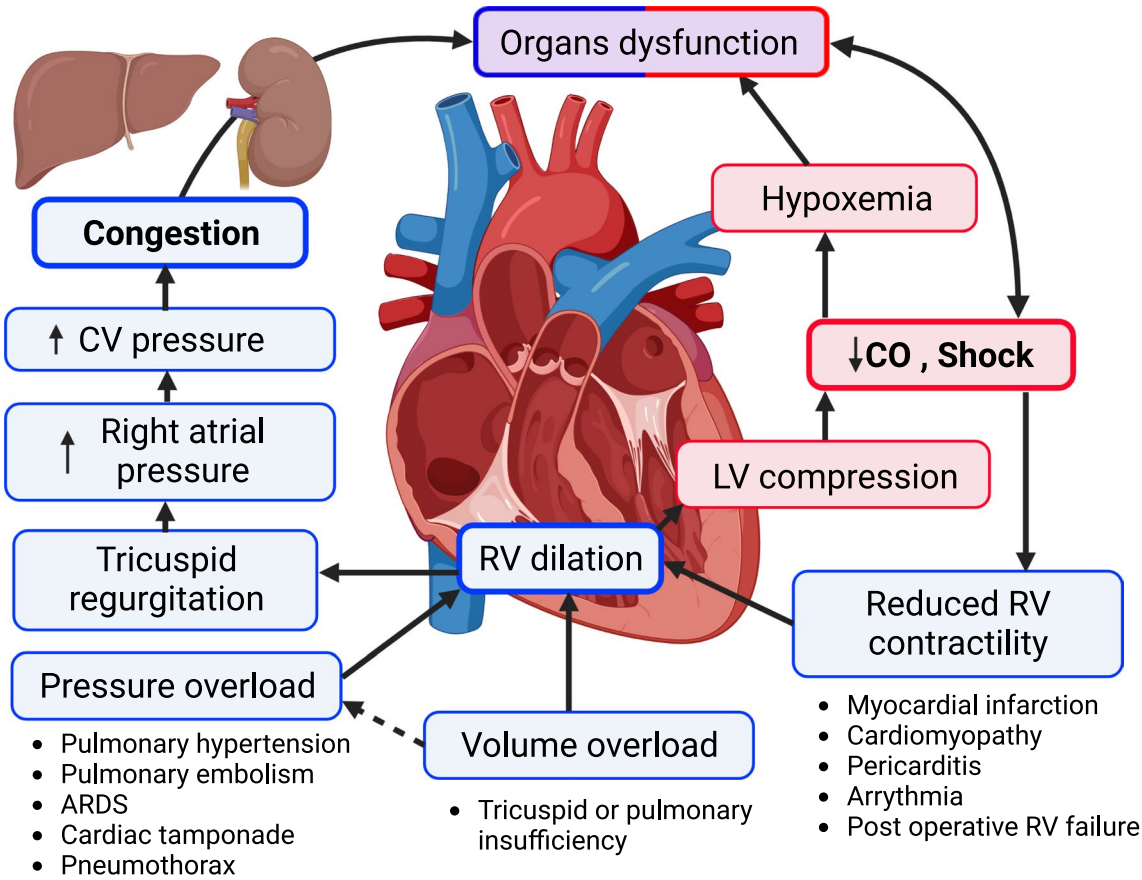

Fig. 2 Pathophysiology of acute right ventricular function. RVF right ventricular failure, RV right ventricle (or right ventricular), LV left ventricle (or left ventricular), CV central vein (or central venous), CO cardiac output, ARDS acute respiratory distress syndrome

In the event of reduced myocardial contractility, increased pressure, and/or volume overload of the RV, compensatory mechanisms to maintain constant blood ejection of RV will rapidly be set up. The heterometric adaptation initially described by Starling defined as an increased contractility of stretching myocardial fibers is the first compensatory mechanism put in place. Secondly, homomeric adaptation increases the myocardial contraction force by increasing myocardial calcium transient [24]. Despite these rapidly implemented compensatory mechanisms and in the absence of immediate treatment of the cause of RVF, the RV will rapidly dilate (with the appearance of tricuspid regurgitation, (TR)) leading rapidly to a reduction in right and left blood ejection. Precipitating factors of acute RVF include mechanical ventilation (increasing transpulmonary pressure (alveolar-pleural pressure), reduced RV stroke volume, and CO [25, 26]), hypoxemia [27] and hypercapnia [28] (by acting on the state of contraction of the pulmonary vessels, increase vascular resistance and therefore pulmonary artery pressure (PAP)), and an excessive vascular filling (increasing RV dilation, right atrial pressures, and congestion of the upstream organs (liver and kidney)).

Epidemiology of Acute RVF

The prevalence of acute RVF is difficult to estimate mainly due to the lack of a precise and clear definition of this condition.

The occurrence of acute RVF is associated with poor outcomes, namely high in-hospital mortality rates ranging from 5 to 7% according to studies [9]. Etiologies of acute RVF are various. The three main causes of acute RVF includes MI, PE, and ARDS in 30 to 50% of cases [29]. Acute RV myocardial infarction (RVMI) is typically seen in patients with acute inferior MI and is reported to be present in more than 50% [30]. In the *SHOCK* trial, where patients with MI complicated by cardiogenic shock were enrolled, predominant RVF was observed in 5% of patients [31]. Acute PE can cause acute RV strain because of pressure overload [15]. Acute RVF is reported to be present in 25 to 60% of patients with acute PE [32, 33] [15]. The occurrence of acute RVF during ARDS is a major risk factor of -ICU mortality [34].

Infectious etiologies of acute RVF are various. In a prospective study of patients with myocarditis, the presence of RV dysfunction diagnosed by cardiac magnetic resonance imaging (MRI) was associated with a hazard ratio of 3.4 for death or heart transplantation and was the strongest predictor of death [35]. Arrhythmias such as atrial fibrillation and atrial flutter are often associated with RV pressure overload, and can negatively affect RV filling [3]. Post-surgical acute RVF occurs during or after noncardiac surgery due to myocardial ischemia [15], secondary to hypoxia, microemboli, arrhythmias, and excessive fluid loading [15]. However, its incidence is difficult to determine. More than 20% of patients with implanted isolated left ventricular assist device (LVAD) experience acute RVF, which is a leading cause of premature morbidity and mortality [36–38]. The implantation of LVAD increases venous return and RV preload, which leads to a collapse of RV function, RV dilation, TR, leftward shift of the interventricular septum, and a reduced RV stroke volume [15].

Diagnosis of Acute RVF

The diagnosis of RVF is challenging since there is no specific sign of the condition and often various signs co-exist. Of note, TTE is the key exam for the diagnosis and the severity assessment of acute RVF. Biology is often used to detect organ dysfunction and to precise the etiology of acute RVF. Clinical signs, biology, and TTE parameters are summarized in Table 1.

Clinical Signs of Acute RVF

Clinical signs of acute RVF are summarized in Table 1. The clinical presentation of acute RVF is heterogenous, depending on its etiology, of the presence of systemic congestion and organ dysfunction. In the most severe cases, patients with acute RVF can present signs of cardiogenic shock (e.g., tachycardia, hypotension, skin mottling, oliguria/anuria, encephalopathy, cold extremities) [15].

Biology

There is no specific biomarker for the diagnosis of acute RVF [1]. Biological assays are mainly used for etiological diagnosis (e.g., troponinemia in MI). Impaired renal function (with increased serum creatinine and blood urea nitrogen associated with a decreased glomerular filtration rate (GFR)) and liver function (increased serum alanine transaminase and serum aspartate transaminase, increased lactate level, and decreased coagulation factors) are observed in case of severe congestion [9]. Finally, while the B-type natriuretic peptide (BNP) is nonspecific to RVF [39], several studies found an association between BNP levels and outcomes in patients admitted for PAH with acute RVF[26, 40, 41].

Electrocardiographic Evaluation

Acute RVF is often associated with sinus tachycardia. In addition, electrocardiographic signs associated to the etiology (e.g., PE) can be found. Finally, atrial arrhythmias are frequent [15].

Table 1 Signs and parameters of RVF

Clinical signs of RVF

➢ Signs of congestion
- Jugular venous distention
- Hepato-jugular reflux
- Congestive hepato/splenomegaly
- Ascites
- Peripheral edema
- Pericardial effusion

➢ Signs of reduced cardiac output
- Tachycardia
- Hypotension
- Skin mottling
- Cold extremities
- Oliguria/anuria
- Encephalopathy

Biological parameters of RVF

➢ Cardiac biomarkers
- Increased natriuretic peptides (BNP, NT-proBNP)
- Increased troponin

➢ Hypoperfusion and/or congestion of organs
- Increased plasmatic arterial lactate level
- Increased serum creatinine and BUN, decreased eGFR
- Increased AST, ALT, total and indirect bilirubin
- Decreased coagulation factors production (prolonged PT)

Transthoracic echocardiographic parameters of RVF
- **TAPSE < 17 mm**
- **FAC < 35%**
- **Systolic S' velocity of the tricuspid annulus < 9.5 cm/s**
- Pericardial fluid > 5 mm in diastole
- RV wall thickness > 5 mm
- IVC diameter > 21 mm and inspiration collapse < 50%
- TR peak systolic velocity > 2.8 m/s
- RV/LV end-diastolic diameter > 1.0
- RV basal diameter > 41 mm, ventricular independence (septal shift, D-shaped LV)
- Longitudinal strain of RV free wall < 20%
- RIMP > 0.54
- 3-dimensional RV ejection fraction < 45%

Right heart catheterization parameters of RVF
- Elevation of CVP greater than 20 mmHg
- Inversion of CVP- PCWP gradient (CVP > PCWP)
- Low CI (< 2 L/min/m^2)
- Low SVI (< 30 mL/m^2)
- Decreased of SvO_2 (< 55%)

Values in bold indicates are the three parameters recommended by the American Society of Echocardiography and the European Assicuatuib of Cardiovascular Imaging that at least one of these be quantitatively evaluated

RVF right ventricular failure, *BNP* B-type natriuretic peptide, *NT-proBNP* N-terminal B-type natriuretic peptide, *BUN* blood urea nitrogen, *eGFR* estimated glomerular filtration rate, *AST* aspartate transaminase, *ALT* alanine transaminase, *PT* prothrombin time, *TAPSE* tricuspid annular plane systolic excursion, *FAC* fractional area change, *RV* right ventricular, *IVC* inferior vena cava, *TR* tricuspid regurgitation, *LV* left ventricular, *RIMP* RV index of myocardial performance, *CVP* central venous pressure, *PCWP* pulmonary capillary wedge pressure, *CI* cardiac index, *SVI* stroke volume index, SvO_2

Transthoracic Echocardiographic Signs and Parameters

Transthoracic echocardiography is a safe and reproducible exam for the diagnosis and severity assessment of acute RVF. Echocardiographic signs a various and may all not be present (Table 2). A RV dilation (defined by a RV/LV ratio > 0.6 [1, 9, 42]) with loss of the triangular conformation of RV ((its shape rounding at the apical 4-chamber view) associated or not dilation of the inferior vena cava (IVC) is frequently observed [42]. In the case of severe acute RVF with prominent RV dilation, a paradoxical septal motion can be observed [9]. The presence of hypokinesia and/or dyskinesia certifies myocardial damage Bubble study is strongly recommended in the echocardiographic evaluation of acute RVF, notably for the research of a patent foramen ovale, a direct indicator of increased RV filling pressures.[27].

Table 2 Current ongoing trials

Trial name	NCT number	Intervention	Primary outcomes	Number of patients expected	Country
Assessment of Peripheral Veins Doppler Ultrasound for Diagnosis of Acute Right Heart Failure in Suspicion or Follow-up of Pulmonary Hypertension	NCT04792879	Clinical trial Diagnostic test; peripheral vein Doppler ultrasound	Sensitivity, specificity, positive and negative likelihood ratios of venous stasis index, measured by pulsed Doppler on common femoral veins, as a diagnostic criterion for ARHF (defined by RAP ≥ 10 mm Hg)	110	France
A Prospective, Multicenter, Observational, Investigator Initiated Study, Aiming at Serial Multiparametric Evaluation of Right Ventricular Function to Predict Optimal Management Strategies, of Right Heart Failure After LVAD Implantation	NCT03552679	Observational Prospective Case-only Diagnostic test; echocardiography	Moderate or severe RHF within 12 months	600	Germany, Hungary, Italy, Kazakhstan, Netherlands, Turkey, UK
Detection of Right Ventricular Dysfunction by 2D Strain During Acute Respiratory Distress Syndrom (ARDS)	NCT01757522	Observational Prospective Cohort	Detection of RVD by 2D strain compared to standard echographic parameters	47	France
Open Lung Strategy, Gas Distribution and Right Heart Function in ARDS Patients: an Open Lung is a Better Heart	NCT03202641	Clinical trial PEEP ARDSnet vs PEEP LRM	Describe the airways driving pressures (defined as plateau pressure minus PEEP) during "PEEP ARDSnet" (low PEEP/ high FiO2 table) and "PEEP LRM (lung recruitment maneuver followed by PEEP guided by transpulmonary pressure)"	50	US

RAP right atrial pressure, *LVAD* left ventricular assist device, *RHF* right heart failure, *RVD* right ventricular dysfunction, *PEEP* positive end-expiratory pressure, FiO_2 fraction of inspired oxygen

Right Heart Catheterization

Right heart catheterization is the reference exam for evaluation of acute RVF [1] (measurement of systolic PAP, diastolic PAP, mean PAP, peripheral vascular resistance (PVR), CO, pulmonary capillary wedge pressure (PCWP), right atrial pressure (RAP), and stroke volume (SV)). The right heart catheterization also provides indices of tissue perfusion such as mixed venous oxygen saturation (SvO2). However, due to the invasiveness of the procedure, there has been a shift toward echocardiography in recent years although right heart catheterization does have its advantages, namely in critically ill patients (e.g., mechanical ventilator management, post-cardiovascular surgery), where the accuracy of echocardiography is easily compromised [43]. Hemodynamic parameters observed during acute RVF include the following [1]: increased central venous pressure (CVP) greater than 20 mmHg, inversion of CVP-PCWP gradient (CVP > PCWP), increased right atrial pressure (RAP), and low cardiac index (CI; < 2L/min/m^2) in the most severe cases.

Management of Acute RVF

Given the complexity of the disease and its rapidly fatal course, multidisciplinary management (including cardiologists, pulmonologists, and ICU physicians) in expert centers is often necessary. The emergency is in the etiological diagnosis and severity assessment of the disease to correctly refer the patient. Therapeutic management of acute RVF is based on (Fig. 3):

- General measures
- Treatment of consequences of RVF
- Etiological treatment

General Measures

The goal of the management of acute RVF is to maintain RV function to prevent the evolution to cardiogenic shock. General measures (prevention of increasing RV afterload, maintenance of myocardial contractility, and optimization of RV preload conditions) should therefore be implemented rapidly.

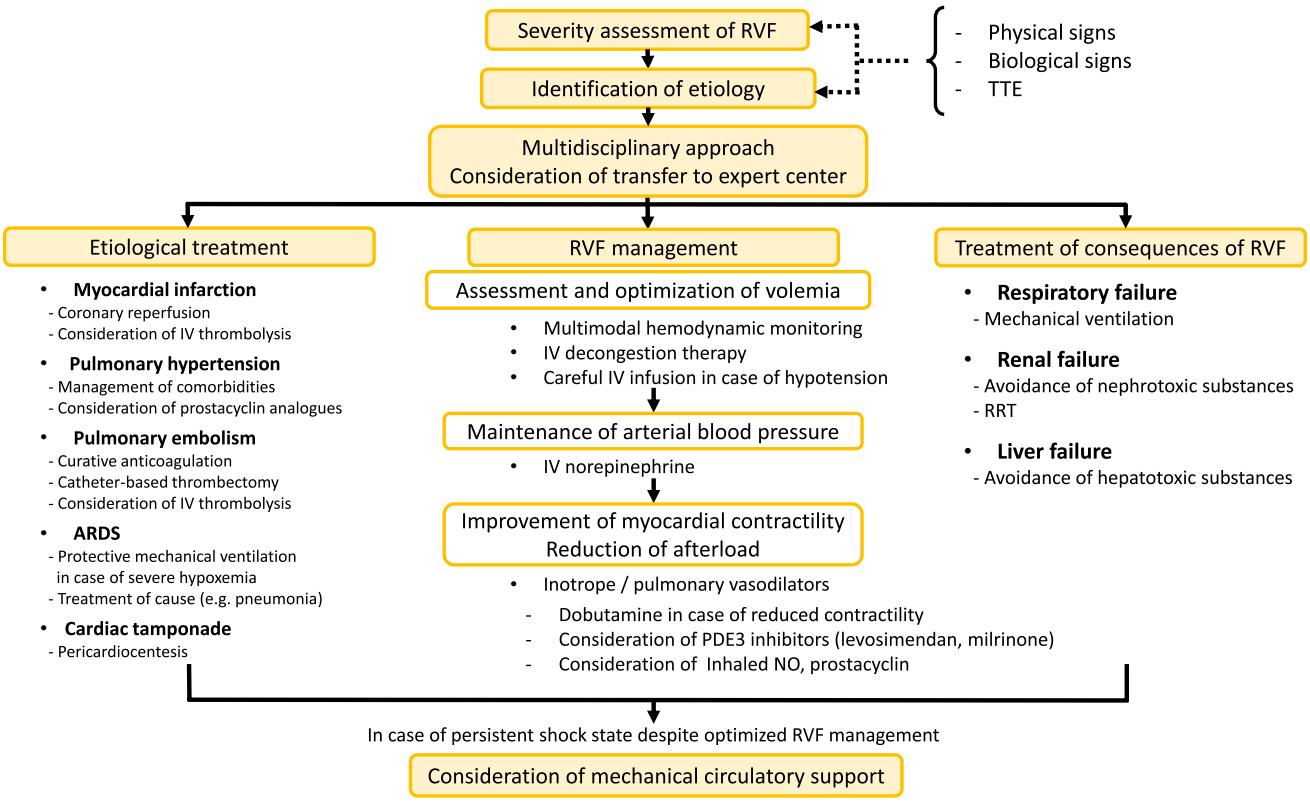

Fig. 3 Acute RVF management. RVF right ventricular failure, TTE transthoracic echocardiography, IV intravenous, ARDS acute respiratory distress syndrome, PDE3 phosphodiesterase III, NO nitric oxide, RRT renal replacement therapy

Assessment and Optimization of Volemia

The failing RV is sensitive to the fluid status during acute RVF. Hypovolemia worsens myocardial ischemia and perfusion of organs already impaired by upstream congestion of failing RV. Hypervolemia results in an increased RV volume, with a risk of aggravation of the paradoxical septal motion in systole. In this case, volume overload (assessed by TTE), decongestion by diuretics, or even renal replacement therapy (RRT) should be initiated without delay. Loop diuretics play a key role for this indication. Continuous infusion after loading doses rather than bolus injection alone of loop diuretics provides the prompt achievement of a steady state of plasma loop diuretic concentration [1]. Furthermore, a combination of the use of loop diuretics with thiazide-like diuretics is indicated whenever diuretic resistance is suspected [1]. In case of abnormal volume status, a close biological (looking for worsening of renal function) and TTE monitoring (regular assessment of volume status, measurement of CO) is necessary. If hypovolemia is suspected, in addition to an echocardiographic examination, fluid challenge associated with right heart catheterization could be considered to estimate the patient's volume status. In case of hypotension associated to hypovolemia, a careful fluid challenge may be tested [44]. If necessary (and only when PCWP is normal), conservative infusion may be required, to restore RV end-diastolic volume and CO. The benefit of infusion when PCWP exceeds 30 mmHg is still controversial [45]. Thus, caution is recommended regarding infusion in patients with suspected RVF.

Mechanical Ventilation

In severe shock or ARDS, airway control and mechanical ventilation are often necessary. The increase in transpulmonary pressure (alveolar pressure—pleural pressure) induced by mechanical ventilation can reduce RV stroke volume (and CO) by increasing RV afterload conditions. If necessary, mechanical ventilation should be adjusted with low tidal volume (6 ml/kg of ideal weight), low positive expiratory pressure, and limited auto-PEEP by reducing the respiratory rate and increasing expiratory time [7, 46–48]. Inspired fractional of oxygen should be adapted to patient objectives, and to maintain sufficient tissue oxygenation, and to limit the occurrence of hypoxemia (a strong pulmonary arterial vasoconstrictor) but also, to limit the occurrence of denitrogenation atelectasis (responsible for an increase in RV afterload conditions).

Finally, maintenance of sinus rhythm in RVF patients is a critical issue: atrial contraction accounts for 40% of the RV filling (or even more in RVF patients), and thus maintenance of sinus rhythm ensures effective filling [1]. In case of impaired LV ejection fraction with nonsinusal rhythm, amiodarone is the drug of choice. Electric shock must be considered in case of hemodynamic instability [2].

Reducing RV Afterload Conditions

Reducing RV afterload can be achieved by pharmacologic measures and by controlling the vasoconstrictive state of the pulmonary vessels (hypoxemia and hypercapnia as discussed above). Inhaled nitric oxide (NO) and prostacyclin have a direct and selective effect on pulmonary vascular smooth muscle. Inhaled NO has a rapid onset of action and a short half-life. Especially, using NO may be useful in critically ill patients with PH and/or hypoxemia. Following its prolonged administration, a rebound effect on PH has been described upon abrupt discontinuation of NO [49]. Despite its beneficial hemodynamic effects, no association between NO use and prognosis has been found during acute RVF [50].

An alternative to inhaled NO is inhaled prostacyclin. In addition to its vasodilatory agents, prostacyclin is a potent antiplatelet agent. No rebound effect has been described to date. The latest guidelines for the diagnosis and treatment of pulmonary hypertension recently published in 2022 recommend class IIa the use of prostacyclin analogues [51]. Epoprostenol needs continuous intravenous administration and was associated with reduced mortality [52]. Inhaled iloprost also demonstrated a decrease in pulmonary vascular resistance (PVR), which directly affects RV function, in a study in which patients of severe PAH and chronic thromboembolic PH (New York Heart Association functional class III or IV) [53]. Treprostinil is available for subcutaneous, intravenous, inhaled, and oral administration. Subcutaneous, intravenous, and inhaled administration have been shown to improve the symptoms of PAH patients [54–57]. On the other hand, for oral administration, primary endpoint (6-min walk distance) has not shown significant improvement in PAH patients on background therapy with other medications (bosentan and/or sildenafil) [58, 59], and studies are inconclusive.

Improving Right Coronary Perfusion

In case of hemodynamic instability and hypotension, norepinephrine is the vasopressor of choice to restore right coronary perfusion. Norepinephrine dosages should be tailored to the clinical situation. At high doses, norepinephrine has positive inotropic effects to improve myocardial contractility and CI [60]. Few data are currently available on other catecholamines in acute RVF [61].

Improvement of Myocardial Contraction

In case of reduced CO due to impaired myocardial contractility during acute RVF, inotropes should be rapidly

considered to restore peripheral perfusion. Dobutamine does not increase pulmonary vascular resistance at low doses (< 5 g/kg/min) but may rapidly induce tachycardia and hypotension which may in turn result in increased myocardial ischemia [9]. Dobutamine should therefore be combined with norepinephrine to prevent the occurrence of hypotension [1]. Milrinone is a phosphodiesterase III (PDE3) inhibitor that prevents the degradation of cyclic adenosine monophosphate (cAMP), increasing the available intracellular calcium supply [1]. Milrinone improves myocardial contractility but is responsible for peripheral vasodilation that can potentially worsen myocardial ischemia, thus limiting its use for RVF. Levosimendan is a positive inotropic agent that combined PDE3 and calcium sensitizer, acting by increasing the sensitivity of myofilaments to calcium, but has the characteristic of not increasing the cytosolic calcium concentration and is therefore without a negative effect on diastolic function [62]. Furthermore, it does not increase myocardial oxygen consumption in patients with heart failure [62, 63]. In addition, levosimendan induces pulmonary, systemic, and coronary vasodilation through its action on adenosine triphosphate-dependent acid potassium channels [63]. It can therefore potentially lead to a decrease in myocardial perfusion, but due to the dilation of the coronary network, myocardial perfusion is actually increased [63]. This inotropic treatment cannot be considered without initially restoring adequate right coronary perfusion. Further studies are needed to investigate inotropes in acute RVF.

Treatment of Consequences of RVF

Right ventricular failure is associated with an increased risk of developing organ dysfunction, namely liver and kidney failure, due to systemic congestion and hypoperfusion (through a reduced CO). Screening for the impact of congestion on these organs involves monitoring liver function (PT, factor V associated with liver enzymes) and kidney function (serum creatinine, BUN, and GFR assessment). The management of the consequences of RVF includes the avoidance of all potentially hepatotoxic (e.g., paracetamol) and nephrotoxic treatments (e.g., aminoglycosides). There are few specific treatments, and treatment for RVF is the best treatment for these consequences.

Etiological Treatment

Etiological treatment of RVF is a major point in the management of acute RVF and should be initiated as soon as possible. Coronary angiography and reperfusion need to be considered for myocardial infarction, anticoagulation or interventional thrombectomy for pulmonary embolism, and pericardiocentesis for cardiac tamponade. Surgery or catheter-based interventions are quickly needed in case of valvular lesions.

Mechanical Circulatory Support

Knowledge on the benefit of mechanical circulatory support in acute RVF remains limited and no recommendation is available to date. The initiation of mechanical circulatory support in acute RVF can reasonably be proposed when the etiology is reversible (bridge to recovery) or while waiting for a heart transplant (bridge to transplantation). The time to implantation of mechanical assistance before the occurrence of organ failure is the main prognostic factor [64]. Clinical trials comparing the efficacy of these devices with other management are still needed.

Ongoing Trials and Perspectives

Table 2 summarizes ongoing trials related to acute RVF. A study (NCT04792879) exploring the detective power of pulsed Doppler ultrasound of the common femoral vein for acute RVF in the setting of PH may support the diagnosis of ARHF by echocardiography in a more convenient and rapid way. Although a higher risk of occurrence of RVF has been reported in patients after LVAD implantation [65, 66], few studies have studied long-term follow-up with echocardiography. In this regard, an ongoing study (NCT03552679) involving 600 patients will add new insight into the prognosis of post-LVAD implantation patients at high risk of occurrence of RVF. One study (NCT01757522) is attempting to propose the two-dimension (2D) strain as new echocardiographic parameters for the detection of RV dysfunction in patients with ARDS. Assessment of myocardial strain may point to earlier right ventricular problems. In addition, regional contractility patterns may vary with underlying disease [13], so maybe one means of approaching the complex pathogenesis of RVF. In patients with ARDS, the adverse effects of mechanical ventilators on RVF are particularly problematic. Finally, another study (NCT03202641) compares two different strategies for PEEP: a group using a low PEEP/high FiO2 table (PEEP ARDSnet) and a group managed with pulmonary recruitment maneuver followed by PEEP guided by transpulmonary pressure (PEEP LRM).

Conclusion

Right ventricular failure is a clinical syndrome affecting the systemic and pulmonary circulation. Multidisciplinary treatment is needed and transfer to an expert center should be

considered. The primary goal of management is to identify the cause and to assess the severity of the disease. Transthoracic echocardiography plays a central role in the management of acute RVF. Therapeutic management of acute RVF is challenging and includes general measures to maintain RV function and to prevent cardiogenic shock, treatment of the etiology, and consideration of mechanical circulatory support in the most severe cases. However, data are clearly lacking, and further studies are needed to better understand the pathophysiology and to optimize therapeutic management.

Data Availability The dataset generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest Pr. Mebazaa reports personal fees from Orion, Roche, Adrenomed, and Fire 1 and grants and personal fees from 4TEEN4, Abbott, Roche, and Sphyngotec. Dr. Deniau was invited to a meeting in Henningsdorf by 4TEEN4 Pharmaceuticals GmbH. The remaining authors declared no potential conflicts of interest with respect to the research authorship and/or publication of this article. The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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