REVIEW

Right heart failure in the intensive care unit

Clifford R. Greyson

Purpose of review
This review summarizes the approach to and recent developments in the evaluation and treatment of acute right heart failure in the ICU. Right heart failure, defined as failure of the right ventricle to provide sufficient blood flow through the pulmonary circulation at normal central venous pressure, is a common problem caused by a combination of increased right-ventricular afterload and right-ventricular contractile dysfunction.

Recent findings
Management of acute right heart failure continues to be challenging because of insufficient understanding of its pathophysiology, a lack of guidelines, and few available tools. Recent research has contributed to an improved understanding of its mechanisms, helping to guide therapy and suggest future options. Right-ventricular assist devices are emerging as a promising approach to treatment when optimization of hemodynamics and conventional medical therapy fail.

Summary
Right heart failure causes venous congestion and systemic hypoperfusion. Once right heart failure is identified, the primary goal is to alleviate any reversible cause of excessive load or right-ventricular contractile failure. When the underlying abnormalities cannot be alleviated, trials of diuretic, vasodilator, or inotropic therapy may be required. Invasive monitoring helps guide therapy. Medically refractory right heart failure may potentially be treated with right-ventricular assist devices.

Keywords
cor pulmonale, pulmonary hypertension, right ventricle, ventricular assist device

INTRODUCTION

Right heart failure (RHF) is defined as the clinical syndrome in which the right ventricle (RV) of the heart fails to deliver adequate blood flow through the pulmonary circulation at a normal central venous pressure (CVP). Clinical RHF is identified by signs and symptoms of venous congestion due to elevated CVP along with evidence of right-ventricular contractile dysfunction and right-ventricular pressure overload; progressive RHF can cause systemic hypoperfusion. However, RHF is not synonymous with right-ventricular contractile dysfunction, and is not necessarily associated with severe pulmonary hypertension, although pulmonary arterial pressure is usually at least mildly elevated.

The development, normal physiology, and pathophysiology of the RV and the RHF were previously reviewed elsewhere [1,2]. Treatment of chronic pulmonary hypertension, venous thromboembolic disease, interventions for right-ventricular myocardial infarction, and general issues of resuscitation will not be discussed in this review. This review will focus on the cause, evaluation, and management of RHF in the ICU. Experimental studies that provide insight into the pathophysiology of RHF and suggest potential future therapies will also be discussed.

From a practical point of view, management of RHF in the ICU consists of identifying abnormalities of right-ventricular function or pulmonary circulation, addressing any underlying reversible problems, optimizing preload, and utilizing inotropic agents. If these measures fail, the most promising emerging therapy is the use of right-ventricular assist devices (RVADs).

PATHOPHYSIOLOGY AND CAUSE OF RIGHT HEART FAILURE

The RV of the heart differs structurally and functionally from the left ventricle, necessitating a

Department of Veterans Affairs Medical Center and the University of Colorado School of Medicine, Denver, Colorado, USA

Correspondence to Clifford R. Greyson, MD, Cardiology 111B, Denver VAMC, 1055 Clermont Street, Denver, CO 80220, USA. Tel: +1 303 393 2826; fax: +1 303 393 5054; e-mail: Clifford.Greyson@UCDenver.edu

Curr Opin Crit Care 2012, 18:424–431
DOI:10.1097/MCC.0b013e3283577070

KEY POINTS

- Clinical right heart failure is defined as elevated central venous pressure due to a combination of right-ventricular contractile dysfunction and increased right-ventricular afterload.
- The primary approach to management of right heart failure is alleviation of underlying causes of right-ventricular contractile dysfunction and abnormal right-ventricular afterload, followed by optimization of preload and afterload, then judicious use of inotropic agents.
- Invasive hemodynamic monitoring may be necessary to correctly identify reversible causes of right heart failure and to optimize management.
- Right-ventricular assist devices are the most promising emerging therapeutic modality for treatment of medically refractory right heart failure.

fundamentally different approach to RHF from the usual approach to left heart failure. RHF is almost invariably a consequence of a combination of elevated right-ventricular afterload and depressed right-ventricular contractile function, with the relative contribution of these two factors determining the appropriate therapy. Table 1 lists the major conditions that cause elevated RV afterload and RV contractile dysfunction in the ICU.

In contrast to the left ventricle, the RV is optimized for low-pressure flow and to accommodate large dynamic changes in venous return with minimal change in generated pressure or output [3]. Because the pulmonary circulation is normally a very low resistance circuit, moderate or even severe right-ventricular contractile dysfunction does not necessarily cause RHF in the absence of elevated pulmonary arterial pressure. Conversely, in the setting of right-ventricular contractile dysfunction, moderate increases in right-ventricular afterload cause RHF [4]. Once the normal compensatory mechanisms of right-ventricular function reach their limits, CVP rises, leading to venous congestion as the primary manifestation of RHF.

Table 1. Causes of right heart failure

Major causes of right-ventricular contractile dysfunction
Coronary ischemia (usually from right coronary artery disease)
Chronic pulmonary hypertension
Acute pulmonary hypertension
Systemic inflammatory states and sepsis
Drug toxicity
Right-ventricular cardiomyopathy
Major causes of elevated right-ventricular afterload (e.g. 'pulmonary hypertension')
Abnormalities of the pulmonary arterial circulation (WHO type 1 pulmonary hypertension)
Left-ventricular systolic or diastolic dysfunction
Mitral valve disease (mitral stenosis or mitral regurgitation)
Ventricular septal defect
Hypoxic pulmonary vasoconstriction and lung injury
Venous thromboembolic disease

Sudden increases in right-ventricular pressure are poorly tolerated [5]. Even when right-ventricular contractile function is initially normal, severe right-ventricular pressure overload can cause a progressive and persistent decline in right-ventricular function after as little as 90 min, likely due to activation of endogenous proteases [6] or induction of apoptosis [7]. Whereas the RV can in some cases adapt to slowly rising pulmonary pressure, chronically elevated right-ventricular pressure more typically causes progressive adverse remodeling and right-ventricular contractile dysfunction [8]. Prolonged high pulmonary arterial flow can also cause progressive right-ventricular contractile dysfunction and RHF independent of changes in the pulmonary vasculature, possibly due to activation of inflammatory and apoptotic factors in the RV [9▪].

Recently, an increased appreciation of the importance of ventricular–vascular coupling has developed. Abnormal right-ventricular afterload from changes in pulmonary artery stiffness (or compliance) may be as important as abnormalities of pulmonary vascular resistance [10▪,11▪], with a less compliant pulmonary circulation leading to an increase in pulsatile load on the RV, and excessively compliant pulmonary circulation causing dissipation of right-ventricular contractile energy: Vanagt *et al.* [12▪] describe a case of RHF occurring despite apparently normal right-ventricular function and normal pulmonary vascular resistance when a massively dilated pulmonary homograft absorbed rather than transmitted right-ventricular output following a truncus repair in an infant. The problem was corrected by replacement of the pulmonary homograft with a less compliant aortic homograft.

Once RHF develops, elevated intrathoracic pressure from ventilator therapy may exacerbate it; use of high-frequency ventilation with high mean airway pressure is particularly detrimental to right-ventricular function [13].

ASSESSMENT OF RIGHT HEART FAILURE

Just as the single most important finding in left heart failure is elevated left-ventricular diastolic

pressure, the single most important finding in RHF is elevated right-ventricular diastolic pressure, which, in the absence of tricuspid valve stenosis, is effectively equal to CVP. When CVP is normal, RHF should rarely, if ever, be diagnosed, even if right-ventricular contractile function appears abnormal on imaging studies. Thus, the first step in the assessment of suspected RHF is determination of CVP.

Estimation of CVP is usually easily accomplished through inspection of the jugular veins, but correct estimation of CVP requires practice and can be challenging [14]. When the jugular veins cannot be clearly identified (such as in very obese or instrumented patients), adjunctive tools such as vascular ultrasound devices can be helpful [15,16▪]. In the absence of elevated CVP, peripheral and visceral edema should not generally be attributed to RHF, and alternative potential causes should be investigated, such as impairment of venous or lymphatic return, hypoalbuminemia, renal failure, capillary leak syndromes, and side effects of drug therapy such as calcium channel blockers. Causes of elevated CVP other than RHF, such as simple volume overload, pericardial tamponade or constriction, left heart failure (either systolic or diastolic), or factitious causes such as superior vena cava thrombosis, should also be excluded.

Absence of pulmonary congestion in the setting of elevated CVP is often considered to be the most specific finding of isolated right-ventricular failure; however, severe pulmonary hypertension may cause elevated left-ventricular end-diastolic pressure and pulmonary edema through interventricular septal shift [17]. Moreover, conditions that are common in the ICU commonly cause physical findings that mimic pulmonary congestion, potentially leading to missed diagnoses. Thus, other more reliable means of assessing left-sided filling pressures are often required.

Imaging

Imaging studies are essential for excluding alternative causes of elevated CVP and assessing right-ventricular size and function. The most readily available imaging technique in the ICU is echocardiography, but in critically ill patients obtaining suitable imaging windows is challenging, and inter-observer agreement on qualitative measures of right-ventricular function is poor [18]. Other modalities, such as magnetic resonance (MR) and cardiac-gated computed tomography (CT), although more accurate, are not always feasible for use in critically ill patients. Several quantitative echocardiographic measurements of right-ventricular contractile function have been shown to correlate more closely with MRI-derived estimates of right-ventricular ejection fraction than visual estimates using 2D imaging, but may be difficult to obtain reliably in critically ill patients [19▪]. At the very least, it should generally be possible to identify significant right-ventricular dilation or contractile dysfunction from a limited number of views and to exclude the major alternative causes of elevated CVP.

Unfortunately, even when good imaging is obtained, interpretation can be difficult: because of the RV's extreme sensitivity to loading conditions, the correlation between right-ventricular ejection fraction and intrinsic right-ventricular function is poor, often leaving in doubt whether the primary cause of RHF is intrinsic right-ventricular contractile dysfunction or abnormal right-ventricular afterload.

Moreover, echocardiography may not be reliable for establishing the relationship between right-ventricular function and systemic hemodynamics. Figure 1 (panels a–d) shows echocardiographic images from a patient who presented with RHF due to chronic thromboembolic disease. On admission, he had severe dyspnea and orthopnea, bilateral lower extremity edema, and a requirement for 10 l O_2 by mask; his SBP was 120 mmHg, and his estimated CVP was 20 mmHg. He was treated aggressively with diuretic therapy, and over the next 2 weeks his weight declined 20 kg with no change in renal function, his exercise tolerance improved, his SBP stabilized at 100 mmHg, and his oxygen requirement declined to 2 l by nasal cannula. Surprisingly, follow-up echocardiography (Fig. 1, panels e–h) showed no apparent improvement in right-ventricular size or function and no change in the paradoxical interventricular septal motion. In this case, it was simple clinical evaluation, rather than advanced imaging, that provided the most reliable guide to ongoing management.

Invasive hemodynamic assessment

Because of challenges in interpreting imaging studies, invasive hemodynamic assessment is frequently necessary in management of RHF. This is particularly true because measurement variability limits the reliability of echocardiographic evaluation of right heart hemodynamics over time [20]. Right heart catheterization provides a direct assessment of CVP and right-ventricular filling pressure and an indirect measurement of left atrial pressure (pulmonary artery occlusive or wedge pressure), helps determine the contribution of left-sided cardiovascular disease to pulmonary hypertension, is used to measure pulmonary vascular resistance to

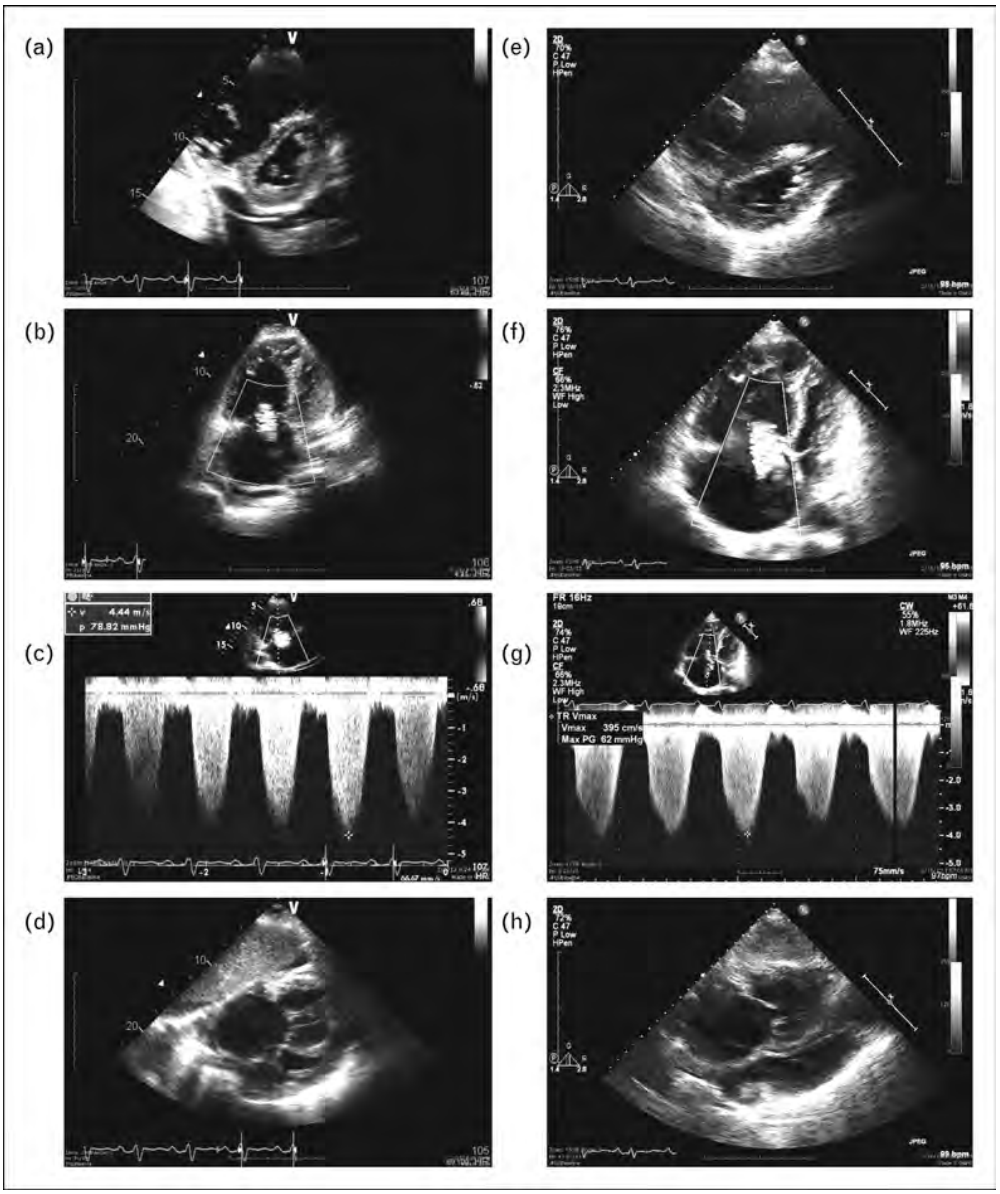

FIGURE 1. Two-dimensional echocardiographic images of a patient with chronic thromboembolic disease and severe right heart failure before (panels a–d) and after (panels e–h) optimization of volume status. The patient presented with severe weight gain, dyspnea, a 10 l/min oxygen requirement and peripheral edema. Panel a is a parasternal short-axis view of the heart, panel b is an apical four-chamber view and panel d is a subcostal view showing severe right-ventricular dilation and compression of the LV by the interventricular septum. Moderate tricuspid regurgitation (panels b and c) revealed a right-ventricular pressure of 78 mmHg plus right atrial pressure (which was estimated to be 20 cm by examination of the jugular veins). After 2 weeks of diuretic therapy, the patient lost 20 kg of weight, he was ambulating with minimal dyspnea, he required only 2 l/min oxygen, and his peripheral edema had resolved. Unexpectedly, repeat echocardiography (panels e–h) showed no significant change in right-ventricular dilation or compression of the LV despite modestly lower right-ventricular pressure (62 mmHg plus an estimated right atrial pressure of 8 cm by examination of the jugular veins). LV, left ventricle.

determine whether pulmonary or systemic vasodilator therapies might be helpful, and provides a reliable means to assess response to therapy.

Caution is required when interpreting pulmonary artery occlusive pressure measurements, because incomplete occlusion by the flow-directed balloon tip can result in falsely elevated pressure measurements [21]. Figure 2 shows hemodynamic measurements obtained from the patient described above at the time of the second echocardiographic examination (Fig. 1, panels e–h), after clinical evaluation concluded that his volume status was optimal. The

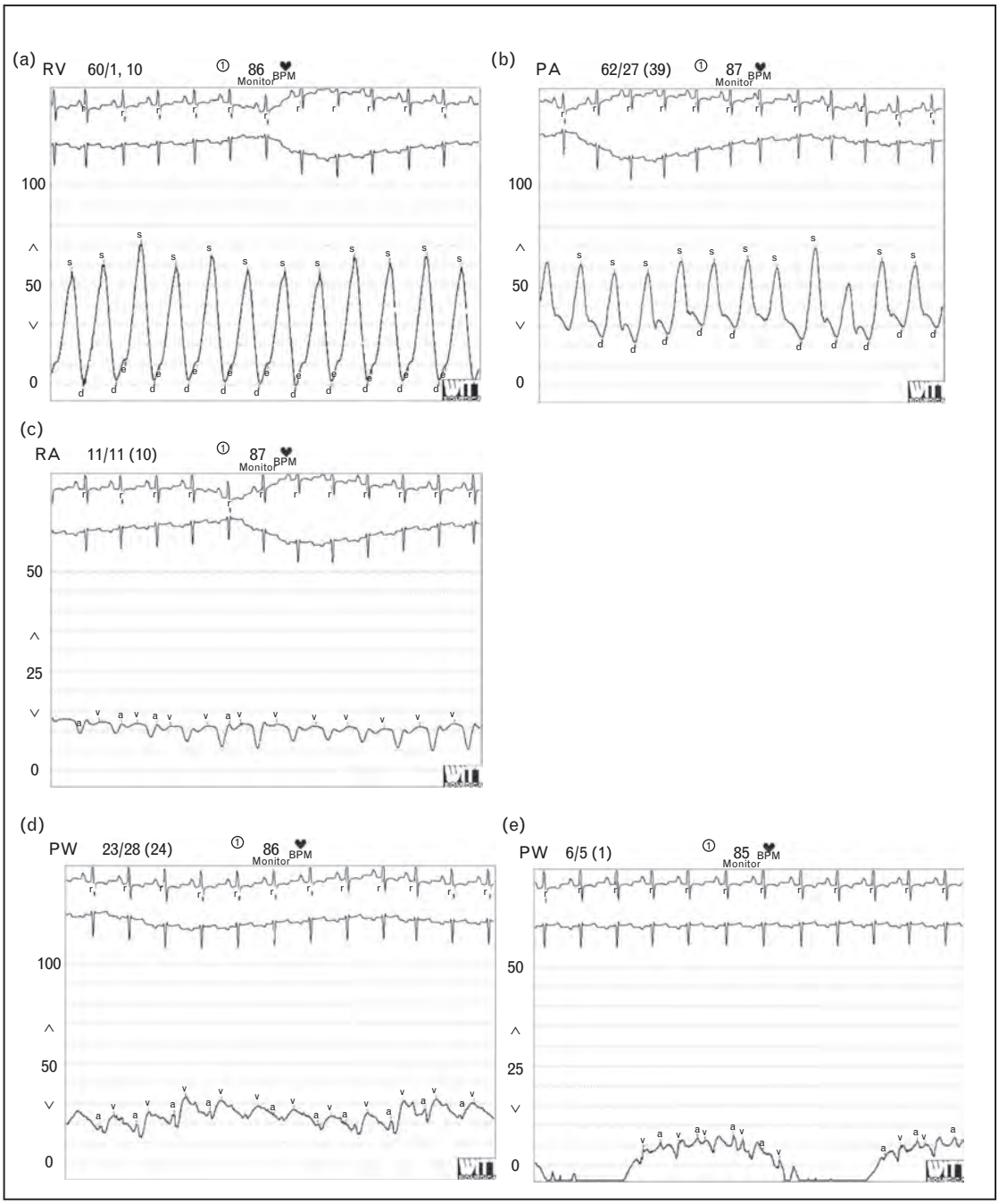

FIGURE 2. Hemodynamic tracings obtained during right heart catheterization from the patient described in Fig. 1 after 2 weeks of diuretic therapy, at a time when clinical evaluation concluded optimization of volume status had been achieved. Panels a–c show right-ventricular pulmonary artery and right atrial pressure tracings. Right atrial mean pressure was 8 mmHg and peak right-ventricular pressure was 62 mmHg, confirming findings by physical examination and echocardiography (Fig. 1, panel g). Panel d shows a tracing obtained after inflation of the pulmonary artery catheter balloon. Initially, it appeared that left atrial pressure was very high (end-expiratory pulmonary artery occlusion pressure was 20 mmHg). Slight repositioning of the catheter resulted in a dramatically different finding shown in panel e (end-expiratory pulmonary artery occlusion pressure of only 8 mmHg), highlighting the difficulty of obtaining reliable estimates of left atrial pressure in patients with severe pulmonary hypertension. Balloon inflation for measurement of pulmonary artery occlusion pressure should be done with caution in patients with severe pulmonary hypertension.

initial measurement of pulmonary artery occlusive pressure indicated high left heart filling pressure, but slight repositioning of the catheter tip resulted in a dramatic change in the measured pressure, confirming that the cause of the pulmonary hypertension was chronic thromboembolic disease and not left heart failure.

APPROACH TO TREATMENT OF RIGHT HEART FAILURE

Once any readily reversible cause of RHF, such as right coronary artery occlusion, pulmonary embolism, toxic drugs, sepsis, and hypoxia, have been addressed to the extent possible, the initial approach to therapy depends on whether the primary hemodynamic problem is reduced right-ventricular contractile function or increased right-ventricular afterload.

When right-ventricular contractile dysfunction is the predominant problem, improvement of right-ventricular output through manipulation of preload should be attempted. Like the left ventricle, the RV can utilize the Frank-Starling mechanism to increase stroke work through an increase in right-ventricular free wall stretch. Thus, volume loading may improve right-ventricular output. However, a relatively flat relationship between right-ventricular surface area and right-ventricular volume means that large changes in right-ventricular volume are required before the Frank-Starling mechanism is recruited. Because the pericardium limits total right-ventricular and left-ventricular volume (at least acutely, before the pericardium can remodel), an increase in right-ventricular volume at the expense of left-ventricular volume may have a net negative effect on overall cardiac output [22]. Conversely, a reduction in CVP often has minimal effect on cardiac output, and in fact alleviation of adverse interventricular interaction may improve cardiac output. Moreover, since right-ventricular contractile failure is directly related to right-ventricular wall stress [23], excessive volume loading can worsen right-ventricular contractile function through right-ventricular dilation. Once CVP has risen above 10–14 mmHg, further volume loading is usually detrimental [24].

A common error in management of RHF in the ICU is to assume that elevated creatinine is due to hypoperfusion, and to respond with volume challenges. Recent data suggest that venous congestion, rather than reduced cardiac output, is a major contributor to renal dysfunction in RHF [25▪], and that reduction of CVP can contribute to improved renal perfusion even if there is no change in cardiac output [26▪]. Ultrafiltration may be a more effective therapeutic option than diuretic therapy in some cases of heart failure [27]; a large National Institutes of Health-sponsored study should provide more definitive data about the role of ultrafiltration in heart failure, with enrollment completion expected in the Spring of 2012 [28▪▪].

Once optimal volume status is achieved, if clinically important RHF and systemic hypoperfusion are still present, inotropic agents may be required. Traditionally, dobutamine was considered the agent of choice because of its primary effect on beta receptors with minimal propensity for vasoconstriction, and experimental evidence also showed that dobutamine could improve right-ventricular function without worsening right-ventricular ischemia [29]. However, more recent evidence suggests that levosimendan might be more effective at improving pulmonary hemodynamics, in part through favorable effects on ventricular–vascular coupling [30,31]. Agents with predominant vasoconstrictive activity are conventionally considered to be contraindicated in RHF due to potential pulmonary vasoconstriction and increased right-ventricular afterload, but experimental data suggest that in some cases of RHF they may favorably influence interventricular interaction with a net beneficial effect [32].

When elevated right-ventricular afterload is the primary cause of RHF, measures directed at normalizing pulmonary vascular resistance are preferred. Whereas systemic vasodilators can reverse hypoxic pulmonary vasoconstriction and worsen hypoxemia, a recent case series shows that inhaled nitric oxide can improve hemodynamics and systemic oxygenation in massive pulmonary embolism [33▪]. Sildenafil, which is more commonly used in chronic pulmonary hypertension, appears to have favorable effects on right heart function in the setting of diastolic heart failure [34] and in ventilated patients with RHF due to pulmonary disease [35▪▪].

Although discussion of coronary intervention is beyond the scope of this review, it should be noted that, during right-ventricular infarction from right coronary artery ischemia, atrioventricular node dysfunction may lead to loss of atrioventricular synchrony and worsen cardiogenic shock; in such cases, atrioventricular synchronous pacing is helpful.

MEDICALLY REFRACTORY RIGHT-VENTRICULAR FAILURE: FUTURE DIRECTIONS

Once any underlying cause of right-ventricular contractile failure has been addressed, loading conditions have been optimized, abnormal right-ventricular afterload is improved to the maximum extent possible, and inotropic therapy has been

employed, few additional interventions have established efficacy.

In theory, bypassing the pulmonary circulation might improve cardiac output in cases of elevated right-ventricular afterload. Atrial septostomy has been promoted as a potential therapy for RHF in severe pulmonary hypertension, but, whereas cardiac output may improve, systemic oxygenation probably does not [36,37]. Selectively redirecting deoxygenated venous blood from the pulmonary artery to the lower half of the body via a left pulmonary artery to descending thoracic aorta right to left shunt (Potts anastomosis) has been used successfully in pediatric patients with chronic suprasystemic pulmonary pressure, but, if pulmonary pressure falls, left to right shunt develops, causing an increase in pulmonary flow and worsened pulmonary hypertension. To avoid this problem, Bui *et al.* [38] created a Potts anastomosis with a one-way valve in a porcine experimental model of pulmonary hypertension to allow right to left flow only during episodic increases in pulmonary artery pressure (such as during exercise).

Because right-ventricular pressure overload causes dyssynchronous contraction of the RV and left ventricle with paradoxical septal motion contributing to diminished cardiac output, it would seem that some form of resynchronization therapy might be beneficial, just as it is in left heart failure with a wide QRS complex from left bundle branch block. Preliminary data suggest just such a possibility [39▪▪].

The most promising new approach to RHF is the use of mechanical assist devices. When RHF develops after left-ventricular assist device (LVAD) implantation, several different devices have been employed successfully using either surgical [40▪] or percutaneous [41] implantation. Percutaneously implanted RVADs have also been used as single-chamber device therapy in the setting of primary right-ventricular contractile failure [42▪]; whether these devices are effective in right-ventricular pressure overload failure is not yet established. RV to systemic bypass might be more effective if the bypassed blood were oxygenated. Spillner *et al.* [43▪] tested extracorporeal oxygenation using an RVAD in an ovine model; the clinical feasibility of a similar technique was demonstrated when used in combination with a LVAD [44▪].

Although only animal experimental data are available so far, there are indications that activation of proteases or apoptosis contributes to right-ventricular contractile dysfunction in acute right-ventricular pressure overload, and that certain protease inhibitors attenuate this process [45,46▪]. Whether or not these agents have clinical efficacy is yet to be determined.

CONCLUSION

Right heart failure occurs when the RV of the heart is unable to provide adequate blood flow through the pulmonary circulation at a normal CVP. Careful physical examination, imaging studies, and invasive hemodynamic monitoring are key to identification of reversible underlying causes of right-ventricular contractile dysfunction or elevated right-ventricular afterload. When optimization of preload fails, judicious use of inotropic agents is effective. RVADs are currently employed in some centers and show promise for patients with medically refractory RHF. Further data on the biochemical mechanisms of RHF may lead to new medical therapies in the future.

Acknowledgements

Supported by the Department of Veterans Affairs Medical Research Service.

Conflicts of interest

There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

- ▪ of special interest
- ▪▪ of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (pp. 562–563).

1. Greyson CR. The right ventricle and pulmonary circulation: basic concepts. Rev Esp Cardiol 2010; 63:81–95.
2. Greyson CR. Pathophysiology of right ventricular failure. Crit Care Med 2008; 36:S57–65.
3. Santamore WP, Amoore JN. Buffering of respiratory variations in venous return by right ventricle: a theoretical analysis. Am J Physiol 1994; 267: H2163–H2170.
4. Brooks H, Kirk ES, Vokonas PS, *et al.* Performance of the right ventricle under stress: relation to right coronary flow. J Clin Invest 1971; 50:2176–2183.
5. Guyton AC, Lindsey AW, Gilluly JL. The limits of right ventricular compensation following acute increase in pulmonary circulatory resistance. Circ Res 1954; 2:326–332.
6. Greyson CR, Schwartz GG, Lu L, *et al.* Calpain inhibition attenuates right ventricular contractile dysfunction after acute pressure overload. J Mol Cell Cardiol 2008; 44:59–68.
7. Dewachter C, Dewachter L, Rondelet B, *et al.* Activation of apoptotic pathways in experimental acute afterload-induced right ventricular failure. Crit Care Med 2010; 38:1405–1413.
8. Bogaard HJ, Abe K, Vonk Noordegraaf A, Voelkel NF. The right ventricle under pressure: cellular and molecular mechanisms of right-heart failure in pulmonary hypertension. Chest 2009; 135:794–804.
9. ▪ Rondelet B, Dewachter C, Kerbaul F, *et al.* Prolonged overcirculation-induced pulmonary arterial hypertension as a cause of right ventricular failure. Eur Heart J 2012; 33:1017–1026.

This experimental study provides new insight into the mechanisms that contribute to RHF in the setting of excessive pulmonary arterial flow.

10. ▪ Stevens GR, Garcia-Alvarez A, Sahni S, *et al.* RV dysfunction in pulmonary hypertension is independently related to pulmonary artery stiffness. JACC Cardiovasc Imaging 2012; 5:378–387.

This clinical study shows that right-ventricular function is as dependent on pulmonary arterial stiffness as it is on pulmonary vascular resistance; this may have implications for clinical evaluation of patients with right heart failure not entirely explained by elevated PVR.

11. ▪ Wang Z, Chesler NC. Pulmonary vascular wall stiffness: an important contributor to the increased right ventricular afterload with pulmonary hypertension. Pulm Circ 2011; 1:212–223.

Nice review of methods for investigating mechanical characteristics of the pulmonary circulation that go beyond simple assessment of pulmonary vascular resistance, written by and for biomedical engineers.

12. Vanagt WY, Famaey N, Rega F, Gewillig M. Extreme windkessel effect can ■ cause right heart failure early after truncus repair. Interact Cardiovasc Thorac Surg 2012; 15:181–182.

The physiology of RHF is incompletely understood; this interesting case report underlines the fact that RHF can occur for reasons not commonly appreciated.

13. Guervilly C, Forel JM, Hraiech S, *et al.* Right ventricular function during high-frequency oscillatory ventilation in adults with acute respiratory distress syndrome. Crit Care Med 2012; 40:1539–1545.

14. Eisenberg PR, Jaffe AS, Schuster DP. Clinical evaluation compared to pulmonary artery catheterization in the hemodynamic assessment of critically ill patients. Crit Care Med 1984; 12:549–553.

15. Jang T, Aubin C, Naunheim R, Char D. Ultrasonography of the internal jugular vein in patients with dyspnea without jugular venous distention on physical examination. Ann Emerg Med 2004; 44:160–168.

16. Jang T, Aubin C, Naunheim R, *et al.* Jugular venous distension on ultrasound: ■ sensitivity and specificity for heart failure in patients with dyspnea. Am J Emerg Med 2011; 29:1198–1202.

A widely available portable ultrasound unit can provide useful measurements of CVP noninvasively when physical examination is inconclusive; this is simpler and probably more accurate than estimation of CVP using inferior vena cava dynamics as commonly performed during a full echocardiographic examination.

17. Allemann Y, Rotter M, Hutter D, *et al.* Impact of acute hypoxic pulmonary hypertension on LV diastolic function in healthy mountaineers at high altitude. Am J Physiol Heart Circ Physiol 2004; 286:H856–H862.

18. Ling LF, Obuchowski NA, Rodriguez L, *et al.* Accuracy and interobserver concordance of echocardiographic assessment of right ventricular size and systolic function: a quality control exercise. J Am Soc Echocardiogr 2012; 25:709–713.

19. Mitoff PR, Beauchesne L, Dick AJ, *et al.* Imaging the failing right ventricle. Curr ■ Opin Cardiol 2012; 27:148–153.

This is a very readable and concise review of imaging techniques available for evaluation of the RV.

20. Farber HW, Foreman AJ, Miller DP, McGoon MD. REVEAL Registry: correlation of right heart catheterization and echocardiography in patients with pulmonary arterial hypertension. Congest Heart Fail 2011; 17:56–64.

21. Leatherman JW, Shapiro RS. Overestimation of pulmonary artery occlusion pressure in pulmonary hypertension due to partial occlusion. Crit Care Med 2003; 31:93–97.

22. Belenkie I, Dani R, Smith ER, Tyberg JV. Effects of volume loading during experimental acute pulmonary embolism. Circulation 1989; 80:178–188.

23. Greyson C, Xu Y, Lu L, Schwartz GG. Right ventricular pressure and dilation during pressure overload determine dysfunction after pressure overload. Am J Physiol Heart Circ Physiol 2000; 278:H1414–H1420.

24. Berisha S, Kastrati A, Goda A, Popa Y. Optimal value of filling pressure in the right side of the heart in acute right ventricular infarction. Br Heart J 1990; 63:98–102.

25. Costanzo MR, Jessup M. Treatment of congestion in heart failure with ■ diuretics and extracorporeal therapies: effects on symptoms, renal function, and prognosis. Heart Fail Rev 2012; 17:313–324.

This comprehensive review summarizes what is known about the effects of venous congestion and renal failure, and outlines the therapeutic options.

26. Testani JM, Khera AV, St John Sutton MG, *et al.* Effect of right ventricular ■ function and venous congestion on cardiorenal interactions during the treatment of decompensated heart failure. Am J Cardiol 2010; 105:511–516.

This very provocative study concludes that venous congestion is a more important cause of renal dysfunction than low cardiac output in RHF.

27. Giglioli C, Landi D, Cecchi E, *et al.* Effects of ULTRAfiltration vs. DIureticS on clinical, biohumoral and haemodynamic variables in patients with deCOmpensated heart failure: the ULTRADISCO study. Eur J Heart Fail 2011; 13:337–346.

28. Bart BA, Goldsmith SR, Lee KL, *et al.* Cardiorenal rescue study in acute ■■ decompensated heart failure: rationale and design of CARRESS-HF, for the Heart Failure Clinical Research Network. J Card Fail 2012; 18:176–182.

Venous congestion is a major cause of cardiorenal syndrome, but patients with heart failure are often diuretic resistant. RHF is a major cause of renal dysfunction from venous congestion. Smaller studies have suggested that ultrafiltration is an effective alternative to loop diuretics in left heart failure. This study, when published, should provide conclusive data about whether ultrafiltration should be first-line therapy.

29. Greyson C, Garcia J, Mayr M, Schwartz GG. Effects of inotropic stimulation on energy metabolism and systolic function of ischemic right ventricle. Am J Physiol 1995; 268:H1821–H1828.

30. Kerbaul F, Rondelet B, Demester JP, *et al.* Effects of levosimendan versus dobutamine on pressure load-induced right ventricular failure. Crit Care Med 2006; 34:2814–2819.

31. Morelli A, Teboul JL, Maggiore SM, *et al.* Effects of levosimendan on right ventricular afterload in patients with acute respiratory distress syndrome: a pilot study. Crit Care Med 2006; 34:2287–2293.

32. Apitz C, Honjo O, Friedberg MK, *et al.* Beneficial effects of vasopressors on right ventricular function in experimental acute right ventricular failure in a rabbit model. Thorac Cardiovasc Surg 2012; 60:17–23.

33. Summerfield DT, Desai H, Levitov A, *et al.* Inhaled nitric oxide as salvage ■ therapy in massive pulmonary embolism: a case series. Respir Care 2012; 57:444–448.

This short case series suggests that inhaled nitric oxide may be effective for stabilizing patients with massive pulmonary embolism until more definitive therapy is available.

34. Guazzi M, Vicenzi M, Arena R, Guazzi MD. Pulmonary hypertension in heart failure with preserved ejection fraction: a target of phosphodiesterase-5 inhibition in a 1-year study. Circulation 2011; 124:164–174.

35. Karakitsos D, Papanikolaou J, Karabinis A, *et al.* Acute effect of sildenafil on ■■ central hemodynamics in mechanically ventilated patients with WHO group III pulmonary hypertension and right ventricular failure necessitating administration of dobutamine. Int J Cardiol 2012. [Epub ahead of print]

Sildenafil is inexpensive and well tolerated. This small study suggests it may have efficacy in RHF from pulmonary hypertension, and is worth trying in RHF that fails to improve on conventional medical therapy. Ventilated patients dependent on dobutamine were treated with oral sildenafil, and in many cases could be successfully weaned from dobutamine and ventilatory support.

36. Diller GP, Lammers AE, Haworth SG, *et al.* A modelling study of atrial septostomy for pulmonary arterial hypertension, and its effect on the state of tissue oxygenation and systemic blood flow. Cardiol Young 2010; 20:25–32.

37. Koeken Y, Kuijpers NH, Lumens J, *et al.* Atrial septostomy benefits severe pulmonary hypertension patients by increase of left ventricular preload reserve. Am J Physiol Heart Circ Physiol 2012; 302:H2654–H2662.

38. Bui MT, Grollmus O, Ly M, *et al.* Surgical palliation of primary pulmonary arterial hypertension by a unidirectional valved Potts anastomosis in an animal model. J Thorac Cardiovasc Surg 2011; 142:1223–1228.

39. Hardziyenka M, Surie S, de Groot JR, *et al.* Right ventricular pacing improves ■■ haemodynamics in right ventricular failure from pressure overload: an open observational proof-of-principle study in patients with chronic thromboembolic pulmonary hypertension. Europace 2011; 13:1753–1759.

Resynchronization therapy has been proven to improve left heart failure in several large clinical studies. This study sets the stage for similar trials to be conducted in patients with RHF.

40. Fukamachi K, Shiose A, Massiello AL, *et al.* Implantable continuous-flow right ■ ventricular assist device: lessons learned in the development of a Cleveland clinic device. Ann Thorac Surg 2012; 93:1746–1752.

This is a comprehensive review of one large center's experience with the technical development of RVAD therapy, and surveys the current state of the art.

41. Haneya A, Philipp A, Puehler T, *et al.* Temporary percutaneous right ventricular support using a centrifugal pump in patients with postoperative acute refractory right ventricular failure after left ventricular assist device implantation. Eur J Cardiothorac Surg 2012; 41:219–223.

42. Kapur NK, Paruchuri V, Korabathina R, *et al.* Effects of a percutaneous ■ mechanical circulatory support device for medically refractory right ventricular failure. J Heart Lung Transplant 2011; 30:1360–1367.

This is a case series describing the use of percutaneously implanted RVADs. It provides useful guidance for clinicians interested in using this technique.

43. Spillner J, Stoppe C, Hatam N, *et al.* Feasibility and efficacy of bypassing the ■ right ventricle and pulmonary circulation to treat right ventricular failure: an experimental study. J Cardiothorac Surg 2012; 7:15.

This experimental animal study shows the potential for RVADs in conjunction with extracorporeal oxygenation as single-chamber therapy for treatment of RHF.

44. De Silva RJ, Soto C, Spratt P. Extra corporeal membrane oxygenation as right ■ heart support following left ventricular assist device placement: a new cannulation technique. Heart Lung Circ 2012; 21:218–220.

This clinical report describes a surgical technique that allows RVADs to be used in conjunction with extracorporeal oxygenation in closed chest patients.

45. Mani SK, Shiraishi H, Balasubramanian S, *et al.* In vivo administration of calpeptin attenuates calpain activation and cardiomyocyte loss in pressure-overloaded feline myocardium. Am J Physiol Heart Circ Physiol 2008; 295:H314–H326.

46. Ahmad HA, Lu L, Ye S, *et al.* Calpain inhibition preserves talin and attenuates ■ right heart failure in acute pulmonary hypertension. Am J Respir Cell Mol Biol 2012. [Epub ahead of print]

This is the first study of any agent that attenuates the hemodynamic severity of acute right-ventricular pressure overload-induced RHF by modulating biochemical changes within the right-ventricular myocardium in a large animal model of RHF. Whether or not such agents are useful in clinical RHF remains to be determined.