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Right Ventricular Function and Failure: A Review

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The importance of right ventricular (RV) function in maintaining global cardiac performance is the focus of this discussion. The physiological determinants of normal right ventricular function will be discussed, with particular emphasis on the afterload and contractility characteristics of the right ventricle. Numerous clinical conditions have been shown to affect RV performance. These conditions include positive-pressure ventilation, ischemia, pulmonary hypertension, and cardiac surgery. Present methods for the perioperative evaluation of RV function include angiography, radionuclide techniques, thermodilution techniques, echocardiography, and magnetic resonance imaging. Traditional modalities for the treatment of RV dysfunction consist of pharmacological interventions (i.e., vasodilators and inotropes) and/or mechanical assist devices. Newer pharmacological strategies for the treatment of RV failure and associated pulmonary hypertension include the phosphodiesterase fraction III inhibitors and the prostaglandins, specifically PGE_1. In summary, the accurate evaluation of perioperative RV performance combined with new treatment options will ensure maximal preservation of RV performance.

Attention is presently being focused on the importance of right ventricular function (RV) and the factors that influence right ventricular performance during the perioperative period. Historically, a more complete understanding of RV function has been limited by the perception that the contractile performance of the RV is hemodynamically unimportant. Initial research by Starr et al. reported no detectable impairment on overall cardiac performance with complete destruction of the RV free wall in dogs [1]. New investigations, however, have demonstrated that, in the presence of elevated right ventricular preload or afterload, septic shock, coexistent left ventricular dysfunction or right coronary artery (RCA) occlusive disease, the function of the RV becomes hemodynamically significant [2,3]. As a result, the diagnosis and treatment of RV failure represent a challenging clinical problem.

PHYSIOLOGY OF RIGHT VENTRICULAR FUNCTION

The importance of right ventricular function becomes apparent during the intrauterine period, when it serves as the predominant ventricle. As a result of the foramen ovale and the ductus arteriosus, the right ventricle shares a similar preload and afterload with the left ventricle but ejects approximately 66 percent of the

Abbreviations: ARDS: adult respiratory distress syndrome EKG: electrocardiogram IVS: interventricular septum LAD: left anterior descending LV: left ventricular LVAD: left ventricular assist devices LVEDV: left ventricular end diastolic volume NMI: nuclear magnetic imaging PABC: pulmonary artery balloon counterpulsation PAH: pulmonary artery hypertension PCWP: pulmonary capillary wedge pressure PEEP: positive end-expiratory pressure PVR: pulmonary vascular resistance RA: right atrium RCA: right coronary artery RV: right ventricular RVEDP: right ventricular end diastolic pressure RVEF: right ventricular ejection fraction RVMI: right ventricular infarction

cardiac output. During this early stage of growth and development, the total coronary blood flow to the left and the right ventricle is similar, and flow per gram of myocardium is identical [4]. With the decrease in pulmonary vascular resistance (PVR) that occurs at birth (with the closure of the foramen ovale and the ductus arteriosus), however, the work of each ventricle dramatically changes. This decrease in PVR is accompanied by a reduction in RV pressure and coronary blood flow, with a concomitant increase in left ventricular (LV) myocardial blood flow. As a result, the left ventricle quickly develops into a thick-walled, highly contractile chamber. In contrast, the right ventricle becomes a thin-walled, highly compliant, but poorly contractile chamber.

The blood supply to the right ventricle is derived predominantly from the right coronary artery (RCA), which supplies the right ventricular free wall on the posterior, right lateral, and anterior surfaces of the heart. In addition, the RCA also supplies the inferior one-third of the interventricular septum. Moreover, the RV also receives blood supply from the left anterior descending (LAD) branch of the left coronary artery. The LAD is also responsible for supplying part of the anterior left ventricular free wall and the anterior two-thirds of the interventricular septum. The timing of right coronary blood flow is unique, in that flow occurs during both diastole and systole [5]. This process is in contrast to the LV, which receives the majority of coronary flow only during diastole. Many authors have proposed this "dual source" of RV coronary blood flow as a reason for the relatively small percentage of significant RV dysfunction that is seen even with significant occlusion of the RCA.

Unlike the LV, which has a relatively simple mechanism of contraction, the contraction pattern of the right ventricle occurs in three distinct phases [6]. The first involves contraction of the spiral muscles. The second involves movement of the RV free wall toward the interventricular septum. Finally, the third phase is completed as the left ventricle contracts, causing a "wringer" action which further aids in emptying the right ventricular cavity.

Right ventricular performance is influenced both by intrinsic factors such as the contractile state of the RV myocardium and by extrinsic factors. These extrinsic factors include: preload, afterload, constraining effects of the pericardium, intrapericardiac pressure, right coronary artery perfusion pressure, left ventricular performance, and the contractile state of the interventricular septum. Therefore the maintenance of normal RV function depends both on those intrinsic factors that determine RV contractile performance and extrinsic factors which determine RV pump performance. As such, under certain loading conditions, failure of the RV as a pump may occur in the absence of any depression in myocardial contractility. Conversely, the presence of depressed myocardial contractility may be obscured by favorable loading conditions, resulting in no discernible impairment in RV pump function.

Right ventricular function is exquisitely sensitive to any increases in afterload [7]. The thin-walled right ventricular cavity compensates poorly for any such increases. In comparison to the left ventricle, which maintains a relatively constant output over a wide range of afterloads, the output of the RV abruptly decreases with minimal alterations in afterload (Fig. 1) [7]. Clinically, this process becomes manifest as a progressive decrease in RV ejection, which has particular significance in situations where increases in RV afterload (i.e., increased pulmonary artery pressure or

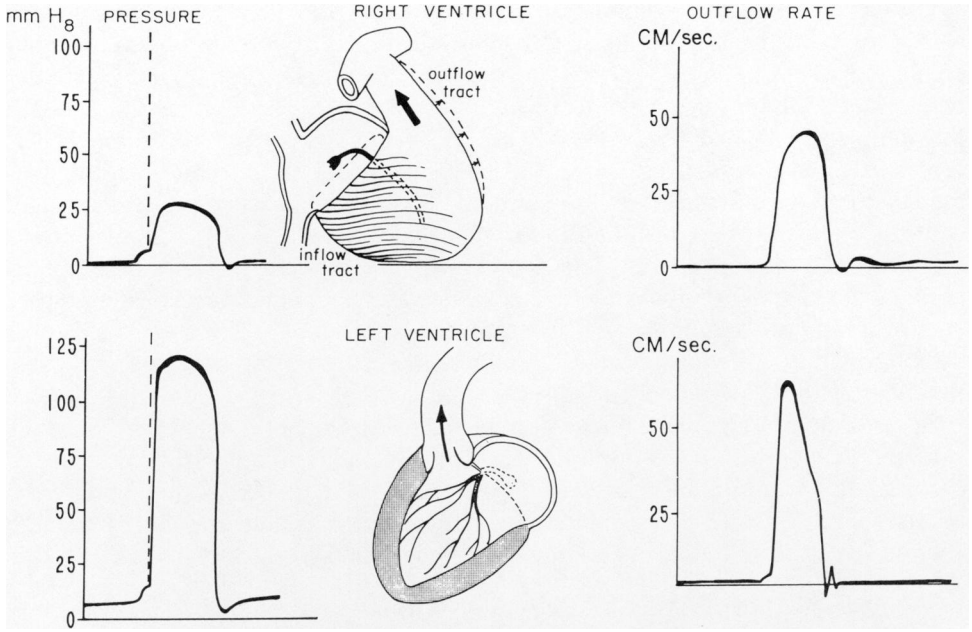

FIG. 1. The effects of varying afterload and preload are seen in these ventricular function curves from the right and the left ventricle. As a result of the highly compliant nature of the RV, afterload changes are poorly tolerated. As may be seen from this figure, even small increases in RV afterload result in dramatic decreases in RV function (as measured by a decreased stroke volume). (Reproduced with permission from [6].)

increased pulmonary vascular resistance) occur. Such conditions would include management of patients with pulmonary artery hypertension, pulmonary embolus, mitral valve disease (with secondary pulmonary artery hypertension), and the adult respiratory distress syndrome.

MECHANISMS OF VENTRICULAR INTERDEPENDENCE

Although the interventricular septum (IVS) is usually considered functionally part of the left ventricle, Taylor and other investigators have shown the importance of the functional interaction between the left and right ventricles by means of the location of the interventricular septum [8]. This interaction results in alterations of the diastolic and systolic function of each ventricle. In a canine preparation, with the right ventricle distended by 50 ml of blood, aliquots of blood presented to the left ventricle were associated with a progressive increase in the right ventricular end diastolic pressure. Similarly, removal of blood from the right ventricle reduced left ventricular pressure. This relationship may have great clinical importance, as defined in the work of Laver and colleagues, who adopted the term "ventricular interference" or ventricular interdependence to describe the importance of the location and contractility of the interventricular septum in maintaining normal cardiac geometry [9]. The hemodynamic effect of this ventricular interaction is more pronounced with the pericardium intact, although more subtle changes are seen when the pericardium is removed [10,11].

Ordinarily, increased pulmonary capillary wedge pressure (PCWP) associated with a decreased cardiac output is diagnostic of left ventricular failure. Under conditions where pulmonary artery pressure is increased, however, right ventricular end diastolic volume and pressure are also increased. This change results in a shift of the interventricular septum into the left ventricular cavity and reduction in left ventricular end diastolic volume. In this particular case, rather than functioning as part of the left ventricle, the interventricular septum is physiologically associated with the right ventricle, resulting in an "internal tamponade." In a clinical study, using two-dimensional echocardiography, Jardin and colleagues showed the importance of this mechanism for reduction in cardiac output of patients receiving positive end expiratory pressure in an intensive care unit [12].

Abnormalities of left ventricular function such as coronary artery disease, congestive heart failure, valvular heart disease, and systemic hypertension all influence right ventricular function, depending on the degree to which they affect RV diastolic volume, RV systolic function, and RV afterload. In addition, the systolic pressure of one ventricle will influence the systolic pressure of the other. In an experimental animal, acute obstruction to left ventricular outflow (without any change in the volume status), resulted in an elevated right ventricular systolic pressure [13].

THE DIAGNOSTIC EVALUATION OF RIGHT VENTRICULAR PERFORMANCE

Any system which allows for the routine measurement of RV volumes would enhance diagnostic capabilities and lead to the development of new therapeutic strategies for the treatment of RV dysfunction. In the past, central venous pressure measurement has served as the "gold standard" for recording RV pressure and volume measurements. Depending upon the compliance changes of the RV and/or abnormalities in the tricuspid valve apparatus, however, central venous pressure may be an inadequate predictor of changes in right ventricular end diastolic volume and pressure. In addition, the poor correlation between ventricular end diastolic volumes and ventricular end diastolic pressure relationships (in the left ventricle) has been demonstrated in recent reports by Calvin et al. [14]. Therefore, rather than relying entirely on pressure measurements as a guide to RV performance, the determination of RV volumes is essential in assessing RV performance.

Several of the diagnostic and therapeutic modalities which have been developed for the evaluation of left ventricular volume have been utilized for the measurement of right ventricular volume. Present techniques available for evaluation of RV volume include: angiography, echocardiography, radionuclide methods, thermodilution, and, recently, magnetic resonance imaging. The accurate estimate of RV volumes by angiography relies upon the development of a single geometric model. Because of the anatomic variability of the RV, depending upon the angle from which it is viewed, it has been described as a pyramid, an ellipse, or a tetrahedron; therefore, development of a standardized technique has been difficult. In addition, angiography often poses a significant risk due to the pharmacological properties of currently available contrast media. Also, each study necessitates the injection of an additional osmotic load, which may be poorly tolerated by seriously ill patients.

To avoid some of the problems encountered with angiography, radionuclide techniques (based on time-activity relationships) have been developed. Two commonly employed radionuclear techniques are: the first-pass technique and the

equilibrium-gated pool scan. Both allow the determination of several parameters, including ejection fraction, systolic ejection time, peak filling rates, peak ejection fraction, and rate of contractility [15,16]. The first-pass technique facilitates the measurement of these parameters during a single cycle and is based upon the principles of indicator dilution therapy [14]. The major advantage of the first-pass technique is the spatial separation of the right atrium from the right ventricle, especially in the right anterior oblique projection. Homogenous mixing of the radioactive tracer is necessary, however, for proper performance of this technique. Therefore, any artifacts encountered (for example, dysrhythmias, or tricuspid regurgitation) may invalidate the results obtained with this method. A separate injection of radioactive tracer is required for each first-pass study, and, as a result, patients are subjected to large amounts of radioactive material if several studies are needed. Development of new short half-life tracers such as gold 195m may allow numerous sequential first-pass studies to be performed without the accumulation of the radioactive tracer [17]. The equilibrium-gated pool utilizes labeled red cells for evaluation of right ventricular function and allows repeated measurements with only a single bolus injection of radioactive tracer [18]. By using a computer, approximately five minutes of heartbeats are collected and gated to the electrocardiogram (EKG); an averaged cycle is constructed to represent right ventricular ejection fraction (RVEF). This technique is ideally suited to the perioperative assessment of RV function. Because isotope is present in all four cardiac chambers, however, it is often difficult to separate right atrial from right ventricular activity, resulting in an inaccurate measurement of RVEF (often as much as 20 percent) [18]. Despite their limitations, these two radionuclear methods have been used quite effectively for the evaluation of perioperative right ventricular function.

In addition to the above-mentioned radionuclear techniques, both M-mode and 2-D echocardiography have been employed to investigate right ventricular function [19]. Ultrasound provides useful information regarding RV dimensions and the movement of the IVS; however, echocardiographic assessment of the right ventricle has several limitations. These difficulties are related to the shape of the right ventricular cavity and the fact that its location is directly below the echo-dense sternum, which acoustically "hides" the RV. The development of 2-D transesophageal echocardiography may allow a more precise visualization of the RV, but this problem warrants further investigation [20].

A new technique has been developed for the determination of RV volumes, one which combines the principles of the indicator dilution theory and use of a rapid-response thermistor pulmonary artery flow catheter [21]. Kay and colleagues have validated this technique, using radionuclear studies both in an animal model and in patients following open heart surgery [22]. The response of the standard thermistor-tipped pulmonary artery catheter is between 300 and 1,000 milliseconds. This catheter is equipped with a "rapid-response" thermistor (50-millisecond), which provides the measurement of temperature variation. A typical thermal washout cardiac output curve generated by this method allows the measurement of changes in temperature associated with successive diastolic plateaus (Fig. 2). Computation of the right ventricular ejection fraction (RVEF) is then easily performed. (Normal thermodilution RVEF is approximately 40 percent.) RVEF, stroke volume, end diastolic volume, and end systolic volume may be easily calculated.

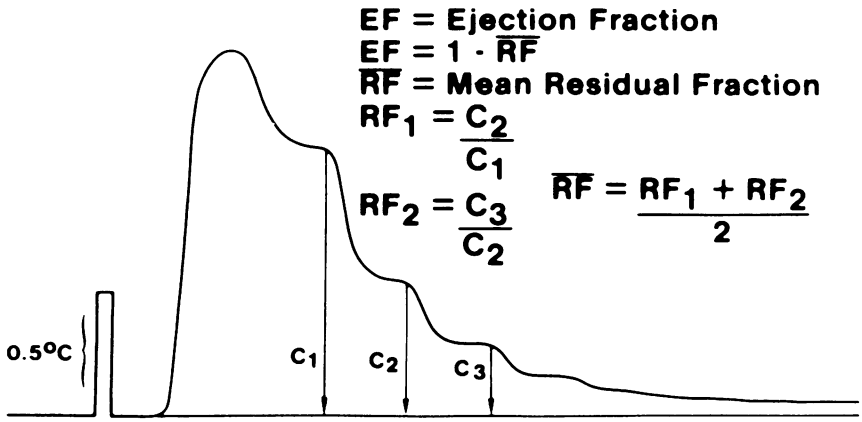

FIG. 2. A representative thermodilution cardiac output curve obtained with rapid-response thermistor pulmonary artery catheter (50 msec). C_1, C_2, C_3 represent temperature differences between successive diastole plateaus. **RF** = residual fraction; **EF** = ejection fraction. (Reproduced with permission from [22].) Using an algorithm right ventricular fraction (RVEF), measures are easily calculated. Normal RVEF by this technique = 40 percent.

$$\text{stroke volume} = \frac{\text{cardiac output}}{\text{heart rate}}$$

$$\text{end diastolic volume} = \frac{\text{stroke volume}}{\text{ejection fraction}}$$

$$\text{end systolic volume} = \text{end diastolic volume} - \text{stroke volume}$$

Thus, from a standard RVEF catheter, the clinician will gain knowledge of cardiac output, right ventricular ejection fraction, pulmonary artery and capillary wedge pressures, and right ventricular pressures as well as right atrial pressure.

There are, however, two specific limitations to the use of this technique. The first involves patients with cardiac dysrhythmias, such as atrial fibrillation; variations in diastolic filling time may introduce errors into the measurement of right ventricular ejection fraction. The right ventricular ejection fraction is computed within four to five beats, however, and therefore an average RVEF may be obtained. In addition, in patients with regurgitant valvular lesions, especially tricuspid insufficiency, an erroneous RVEF may be seen, since this technique measures only forward flow. Placement of the thermistor in the atrium will, however, facilitate calculation of the regurgitant fraction.

The technique of nuclear magnetic imaging (NMI) has recently been employed as the newest method for assessing myocardial performance. This technique has been extremely effective in its ability to evaluate RV architecture and size. In addition, the tricuspid valves as well as the end systolic and end diastolic RV volumes are easily visualized. Using this technique, the epicardial surface of the RV is clearly demonstrated, permitting a more qualitative assessment of the complex RV geometry.

CLINICAL IMPLICATIONS

The importance of monitoring RV function becomes apparent in several clinical situations; these include patients with chronic obstructive pulmonary disease, adult

respiratory distress syndrome, patients requiring mechanical ventilation, and patients receiving a protamine infusion. Matthay and Berger have demonstrated RV dysfunction in patients with chronic obstructive pulmonary disease, using radionuclear stress testing [23]. Abnormal elevations in RV systolic and pulmonary artery pressures were noted in these patients in response to exercise.

In the management of patients with adult respiratory distress syndrome (ARDS), knowledge of right ventricular function is also clinically useful [24]. Regardless of the etiology of ARDS, RV dysfunction usually occurs as a result of increasing afterload, secondary to pulmonary artery hypertension. Sibbald et al. examined biventricular function in patients with ARDS and found a negative correlation between right ventricular ejection fraction and the mean pulmonary artery pressure [25]. This increase in pulmonary artery pressure has also been associated with a depression of right ventricular contractility. It has been proposed that, with increasing RV end diastolic volume, an increase in wall stress may develop, predisposing the RV to subendocardial ischemia [19]. The degree of pulmonary artery hypertension necessary for the development of ischemia and resultant RV failure has not yet been determined.

Various modes of mechanical ventilation may also impair RV performance. By increasing afterload, changes in ventilatory mode may influence RV hemodynamics. Jardin et al. have shown that mechanical ventilation with positive end-expiratory pressure (PEEP) (30 cm H_2O) produces a shift of the interventricular septum with paradoxical motion resulting in right heart dilatation and decreased left ventricular chamber size [12]. New data also reveal that, in post-operative ventilated patients, a decrease in RVEF is observed at PEEP levels greater than 15 cmH_2O [26]. Furthermore, changes in ventilatory modes (i.e., intermittent mandatory or assist control) may further alter right heart function. Studies demonstrate that right ventricular ejection fraction is most impaired with assist-controlled ventilation and is least affected by intermittent mandatory or spontaneous ventilation [27]. Recently, high-frequency jet ventilation has been reported to cause less hemodynamic instability than traditional modes of mechanical ventilation. Its effect on right ventricular performance had not, however, been fully evaluated until a recent report by Biondi et al. [28]. They demonstrated the effect of airway pressure on right ventricular ejection fraction. A significant inverse correlation was noted between RVEF (thermal) and increasing amounts of airway pressure delivered by the high-frequency jet ventilator.

The effect of right ventricular ischemia and/or infarction on global cardiac performance is presently being studied. Hines et al. evaluated right ventricular function in patients undergoing coronary artery bypass surgery [20,29]. Based upon angiographic data, patients were classified according to the degree of stenosis present in the right coronary artery (RCA). Subsets were defined as those having less than 90 percent stenosis, or those with greater than or equal to 90 percent stenosis of the right coronary artery. In the group of patients with greater than 90 percent stenosis of the RCA, a statistically significant increase in RVEF was observed, following coronary artery revascularization. In addition, the same subset of patients were at increased risk for development of right ventricular ischemia. The earliest signs of right ventricular dysfunction were manifested as elevations of right ventricu-

lar end diastolic pressure, accompanied by a decrease in RVEF (in the face of a normal PCWP) [30].

The importance of monitoring RV function intra-operatively has been illustrated by reports of RV failure following protamine infusion. Protamine administration has been associated with right ventricular failure and subsequent cardiac decompensation. Numerous studies imply a predominant vasodilating response as the principal event responsible for myocardial dysfunction observed following protamine administration [31]. A report by Lowenstein et al. suggests, however, that pulmonary vasoconstriction (versus systemic vasodilatation) following protamine infusion may be the primary and principal event leading to right ventricular failure [32]. Lowenstein and co-workers described five patients who developed severe hemodynamic instability when intravenous protamine was infused following cardiopulmonary bypass [32]. To ascertain if protamine infusion was associated with alterations in right ventricular performance on an episodic or a consistent basis, Hines and Barash evaluated both right and left ventricular function in patients undergoing open heart surgery [33]. No statistically significant changes in RVEF, systemic blood pressure, mean pulmonary artery pressure, or pulmonary vascular resistance were noted at any point during the study. In the patients undergoing coronary artery bypass surgery, right ventricular end diastolic pressure (RVEDP) did not significantly increase from the baseline. Similarly, in the patients with valvular heart disease, the pre-protamine right ventricular end diastolic pressure continued unchanged throughout the study. These values remained statistically unchanged following protamine infusion. To ascertain whether pulmonary artery hypertension was an additional risk factor, they examined right and left ventricular function in a subset of patients with pulmonary artery hypertension (PAH) greater than 25 mmHg. Even in these high-risk patients, right ventricular performance, as measured by RVEDP and RVEF, failed to reveal any predictable deterioration in RV function during or following protamine infusion. More recent evidence implies an anaphylactoid response, resulting in the activation of the complement cascade as the principal etiology of pulmonary vasoconstriction and RV dysfunction following protamine administration [34].

Patients undergoing cardiac surgery present several unique problems regarding RV performance. In situations where pre-operative RV hypertrophy is the result of chronic pulmonary hypertension, the RV will have a limited ability to respond to even minimal increases in pulmonary resistance. Cooling of the RV is technically difficult, due to the accumulation of non-coronary collateral blood in the RA and RV. Also the RV is (from the thesbeian veins and bronchial system) more susceptible to ambient temperatures and subsequent rewarming by radiant energy from room lights and manual manipulation. In addition, direct injuries to the right atrium (RA) and RV are common as a result of direct or indirect mechanical trauma. Following cardiopulmonary bypass, the institution of positive-pressure ventilation may impose high levels of pressure on an already non-compliant pulmonary vasculature, resulting in acute RV dysfunction. Finally, intracoronary air is more likely to be distributed to the native RCA artery and/or RCA graft (due to its anterior and superior location) than into the LCA system. Recent reports by Greeley et al. have demonstrated that intracoronary air (following cardiopulmonary bypass) may result in acute intra-operative RV dysfunction [35].

METHODS FOR THE DIAGNOSIS AND DETECTION OF RV ISCHEMIA

Cohn and co-workers first described the clinical sequelae of right ventricular infarction (RVMI) in 1974 [36]. Subsequently, interest in the subset of patients with RVMI has rapidly increased. Although isolated right ventricular infarction is uncommon, there is a high incidence (20–60 percent) of right ventricular involvement in patients with inferior left ventricular infarctions.

The early signs of right ventricular ischemia are often difficult to detect using traditional electrocardiographic lead placement systems. Standard intra-operative monitoring for left ventricular ischemia utilizes a lead V_5 in combination with lead II. Because of the location of the RV, however, this method provides a very limited electrocardiographic view of the right ventricle. New lead placement systems have been developed to increase the specificity and sensitivity for RV ischemia detection. One such system utilizes a V_4R lead (a V_4R lead is placed in the fourth intercostal space in the right midclavicular line). Klein et al. have determined the sensitivity and specificity of using lead V_4R for detecting right ventricular ischemia [37]. Using radionuclide studies and echocardiography to verify the presence of RV dysfunction seen by EKG, they found that a V_4R lead is a highly specific means of monitoring for RV ischemia.

MANAGEMENT OF RV FAILURE

Management of the patient with right ventricular failure remains controversial. Hemodynamics of RV failure include: *(1)* primary increased right atrial and right ventricular end diastolic pressures, *(2)* normal left atrial and left ventricular end diastolic pressures, and *(3)* decreased cardiac output. Treatment strategies have emphasized: *(1)* volume loading, *(2)* vasodilators, *(3)* inotropic support, *(4)* vasoconstrictor, *(5)* mechanical assist devices, and *(6)* maintenance of normal atrioventricular conduction. The appropriate sequences of the therapeutic intervention depend in large part on the status of the pulmonary vascular resistance (i.e., RV afterload).

Volume expansion is the foundation of treatment in situations of RV failure when the pulmonary vascular resistance is normal. This increased volume, in the normal highly compliant RV, will create maximal RV myocardial fiber stretch and maintain cardiac output. In this situation, the dilation of the RV is the major compensatory mechanism for augmenting RV contractility. When volume loading alone is insufficient as diagnosed by (right atrial pressure ≥ 12 mmHg) pulmonary vasodilators and inotropic agents (Table 1), which allow for increased RV contractility and/or pulmonary vasodilatation directly, must be added. The rationale for the treatment scheme is based upon the fact that RV preload will be maximized at a RA $\geq$ 12 mmHg. When an augmentation in preload is insufficient to increase RV performance, then pulmonary vasodilatation or inotropes must be added to maximize RV performance.

Much debate has centered around the practice of using volume expansion as the primary treatment modality in the setting of acute respiratory failure with associated pulmonary hypertension. Prewitt and Ghignone investigated the hemodynamic effects of fluid therapy in the setting of increased pulmonary vascular resistance and ARDS [24]. Using equilibrium scintigraphic techniques, the end diastolic and end systolic areas of both the left and the right ventricles were measured. When pulmonary vascular resistance (PVR) was normal, volume loading resulted in an

TABLE 1
Pharmacological Management of Right Ventricular Dysfunction

Pulmonary Vasodilators	Inotropic Agents
Terbutaline	Dopamine
Oxygen	Dobutamine
Aminophylline	Epinephrine
Prostaglandin (PGE_1)	Isoproterenol
Prostacyclin	Amrinone
Nitroglycerin	Neosynephrine
Amrinone	

increased cardiac output. When increased PVR (PA pressure) was present, however, volume expansion resulted in RV failure, documented by decreasing cardiac output and an increase in right ventricular end diastolic pressure. They postulated that the increases in PVR, in combination with increased RV volumes, resulted in increased RV wall stress and subsequent decreases in RV contractility. Thus, volume expansion further increased myocardial oxygen requirements, leading to RV dysfunction secondary to ischemia. In summary, adult respiratory distress syndrome complicated by pulmonary artery hypertension (PAH), is associated with a reduction in RVEF and an increase in RV end diastolic volumes and may be associated with RV contractile dysfunction. Therefore, in situations where pulmonary vasculature resistance is increased, treatment with pulmonary vasodilators may improve cardiac output by decreasing both RV afterload and PVR and decreasing left ventricular end diastolic volume (LVEDV) [38].

The importance of vasoconstrictor therapy (to maintain RV perfusion pressure) in the treatment of RV dysfunction has been shown by Laver [39]. He produced RV dysfunction in a canine model of myocardial ischemia by a progressive occlusion of the main pulmonary artery. This process was accompanied by a pronounced increase in RVEDP. Infusion of phenylephrine resulted in a dramatic increase in the aortic diastolic pressure, thereby improving right ventricular perfusion. Subsequently, Ghignone et al. supported the efficacy of vasoconstrictor therapy (norepinephrine) in the treatment of low cardiac output associated with elevation in right ventricular afterload [40]. In this animal model with elevated RV afterload (PVR), volume infusion resulted in a decrease in aortic pressure. In contrast, norepinephrine infusion produced a decrease in biventricular filling pressures and an increase in cardiac output. The comparative effects of volume loading, dobutamine, and nitroprusside were evaluated in patients with acute RV infarction [41]. Volume loading alone did not improve cardiac index in these patients, despite a rise in cardiac filling pressures. Following appropriate volume loading, however, the administration of dobutamine produced a significant improvement in cardiac index and RVEF in comparison to those measurements obtained using a combination of volume and nitroprusside. These data illustrate that, if increases in PVR are associated with a reduction in cardiac output, the combination of inotropic and vasodilator therapy will be necessary to restore RV performance.

New modes of pharmacological therapy have been advocated for the treatment of RV failure. D'Ambra et al. have reported their results, using the infusion of

prostaglandin E_1 to dilate the pulmonary vasculature and improve RV function in patients undergoing mitral valve replacement [42]. High doses of PGE_1 were used in combination with left atrial norepinephrine infusion in five consecutive patients with refractory right heart failure and pulmonary artery hypertension. The use of PGE_1 resulted in a reduction of pulmonary vascular resistance and an increase in cardiac index. Recently, the type III phosphodiesterase inhibitors (i.e., Amrinone) have been successfully utilized to reduce PVR and augment RV function in patients undergoing coronary artery bypass surgery and mitral valve replacements [43].

In addition to the pharmacological management of right ventricular dysfunction, the use of mechanical assist devices (right atrial to pulmonary artery pumping) has also been suggested. One such device was initially used to treat post-cardiotomy right ventricular failure [44]. This device costs over $12,000 per pump, however, and its restricted use by the FDA makes it unavailable for most centers performing cardiac surgery. A promising alternative is right atrial to pulmonary artery bypass pumping, using a Bio Medicus (standard roller pump) centrifugal pump. Miller et al. have successfully utilized the pulmonary artery balloon counterpulsation (PABC) device to wean a patient with RV dysfunction from cardiopulmonary bypass [45]. PABC has been effective in RV failure due to pulmonary hypertension, RV infarction, and global cardiac failure. Left ventricular assist devices (LVAD) may also further augment RV performance.

Normal atrioventricular conduction and contraction are essential for maintaining normal RV function. Any loss of sinoatrial activity contributes to a decrease in RV efficiency in much the same way that loss of the atrial "kick" decreases LV efficiency.

As new evidence demonstrating the importance of RV function becomes available, diagnostic and therapeutic strategies will be developed which make possible earlier detection and treatment of right ventricular dysfunction.

Much remains to be learned regarding the assessment of RV performance and the identification of factors responsible for RV dysfunction. Recognizing that the integrity of the RV can be altered by numerous perioperative factors is the first step in developing a systematic approach for monitoring RV function.

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