Low cardiac output due to acute right ventricular dysfunction and cardiopulmonary interactions in congenital heart disease (2013 Grover Conference series)

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Abstract: The importance of right ventricular dysfunction, as a driver of symptoms and outcomes in the normal biventricular circulation, is increasingly recognized. However, the pathophysiologic mechanisms underlying the role of the right ventricle in acute and chronic hemodynamic deterioration are less well understood. This review aims to clarify the impact of acute right ventricular dysfunction on biventricular interactions and, in turn, to discuss the role of cardiopulmonary interactions in the normal circulation and when modified by the presence of associated structural malformations. Such interactions may be adverse or beneficial, and a more complete understanding of their importance may result in novel therapeutic strategies and improved outcomes.

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It is becoming increasingly recognized that right ventricular dysfunction plays a crucial role in many cardiovascular diseases. Even in traditionally “left heart” diseases such as dilated cardiomyopathy, the impact of right ventricular dysfunction on mortality is now well established.¹ It would be surprising, therefore, if the right ventricle (RV) did not play a similarly important role in congenital heart disease. Many congenital heart diseases are characterized by primary abnormalities of right ventricular structure and function, and while “corrective” surgery often restores the heart to a functionally “normal” biventricular circuit, right ventricular hemodynamics are often far from normal. Indeed, the RV frequently remains exposed to highly abnormal loading conditions and is subject to the additional impact of adverse electromechanical, mechanoelectric, and cardiopulmonary interactions.

Consequently, assessment of right ventricular function in congenital heart disease is just as important, if not more so, in the congenitally malformed heart as it is in the otherwise structurally normal heart. In many ways, however, it is more difficult, because the unusual, and sometimes unique, hemodynamics in the congenitally malformed heart challenge the validity of many of the techniques available for assessment. Conversely, congenital heart disease provides us with “natural models” of abnormal right ven-

tricular loading that are difficult to produce in animal models. There is therefore a unique opportunity to better understand right ventricular dysfunction as it is affected by such abnormalities. It is beyond the scope of this review to discuss the impact of the hundreds of different congenital heart malformations and the detailed results of their treatment, particularly when the RV functions as the systemic ventricle. Instead, this review will focus on more general considerations of systolic and diastolic dysfunction in the congenitally malformed subpulmonary RV, especially as it pertains to early postoperative outcomes.

THE NORMAL RV IN A BIVENTRICULAR CIRCULATION

While it is most common, nowadays, to assess ventricular function and ventriculovascular coupling from pressure-volume characteristics, many of the fundamental properties of the ventricle can be assessed from a simple Wiggers diagram. Using this approach, Shaver and colleagues² predicted major differences in the overall contractile pattern of the normal RV and left ventricle (LV). Using simultaneous measurements of ventricular and arterial pressures, they demonstrated the hangout period, a delay between the onset of right ventricular pressure decline and pulmonary valve closure, in the normal right heart. The presence

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of a hangout period, which is lost in pulmonary hypertension, implies that unlike the LV, where the aortic dirotic notch (and cessation of ejection) occurs early in the onset of left ventricular pressure decline, there is continued ejection from the RV as its pressure is falling. Consequently, it can be predicted that the RV has a poorly defined phase of isovolumic relaxation. Subsequent direct measurements of right ventricular pressure-volume relationships confirmed these early observations. Before consideration of the effects of congenital heart disease on, for example, RV contractility, a brief discussion of the pressure-volume characteristics of the normal RV is required. Largely consequent upon its low hydraulic impedance, the pressure-volume characteristics of the normal RV are quite different from those of its left-sided counterpart.³ While the LV has a square or trapezoidal pattern, with well-defined periods of isovolumic contraction and relaxation, the normal RV exhibits a very different contractile pattern. Figure 1 compares the resting left and right ventricular pressure-volume relationships. In the normal RV, the period of isovolumic contraction is abbreviated, and ejection into the pulmonary vascular bed occurs very early during pressure rise. Following development of peak right ventricular pressure, another important difference can be seen. As predicted by Shaver,² the RV continues to eject during its pressure decline.

This has two important consequences. First, unlike the LV, which has a well-defined end-systolic point, usually at the upper left-hand corner of the pressure-volume relationship (minimum cavity dimension, maximal cavity pressure), the normal RV has no such definition of an end-systolic point. This may have important consequences for assessment of contractility in the normal RV. Indeed, the

applicability of the elastance model of ventricular contractile function⁴ may be undermined by the unusual pressure-volume characteristics of the RV, and when traditionally measured as an end-systolic elastance, this may be the case. However, if maximal elastance is measured (the slope of the relationship between maximal pressure and volume), then characteristic changes in the elastance slope with inotropes and beta blockade can be measured.⁵ Nonetheless, studies that purport to measure the end-systolic elastance and single-beat methods that have been derived from the normal left ventricular pressure volume characteristic should be interpreted with caution. Second, the dependence of RV ejection on a low hydraulic impedance makes it exquisitely load dependent. Unlike the LV, where compensatory mechanisms maintain stroke volume over a relatively broad range of afterload, the right ventricular stroke volume is far more sensitive to even relatively modest changes in hemodynamics.⁶

There are several “natural” experiments that emphasize the dynamic nature of these pressure-volume relationships in response to loading conditions. For example, in the chronically pressure-loaded RV, we have shown that the loops assume a “left ventricular” pattern.⁷ Furthermore, in congenital heart diseases where there is transposition of the great arteries, we have reported that the subaortic RV has a “left ventricular” pattern and that the subpulmonary LV assumes a triangular or trapezoidal “right ventricular” pattern.^{7,8} This emphasizes that it is loading conditions rather than underlying ventricular morphology that drive these changes and underscores that understanding of the impact of these changes is fundamental to the management of right heart failure.

RIGHT-LEFT HEART INTERACTIONS

As discussed above, the emergence of the importance of the RV in the pathogenesis of many cardiovascular diseases has led to a concentrated effort to accurately analyze its performance. Just in the same way as many early studies of LV function ignored the possible impact of associated RV dysfunction, many recent studies of the RV are performed in isolation of events occurring on the left side of the heart. Both approaches are flawed. Neither the LV nor the RV can or should be considered as an isolated unit, because they function as an integrated system. Not only are they enclosed by a common pericardium and share an intraventricular septum, but also the superficial layers of the myocardium are common to both ventricles.⁹ Consequently, events that occur on the right side of the heart have important implications for left heart function, and vice versa. This is no better demonstrated than in the normal heart. We have already discussed the rather unusual

Figure 1. Schematics of the normal right and left pressure-volume relationships. Unlike the left ventricle, the right ventricle has poorly defined isovolumic phases and ejects during pressure decline. See text for details.

contractile pattern of the RV, being able to eject during its pressure decline. This may not be a consequence of only the low hydraulic pulmonary vascular impedance. Indeed, there is compelling evidence that left ventricular contractile force contributes to right ventricular systolic function in a fundamental way. In a series of elegant studies by Damiano and colleagues,¹⁰ using electrically isolated but mechanically contiguous heart preparations, the dependence of right ventricular systolic function and ejection on left ventricular contraction was established. Pacing of the electrically isolated LV (obviating any direct contractile effect on the right ventricular free wall) led not only to a robust right ventricular pressure generation but also to a significant ejection into the pulmonary arteries. The authors concluded that approximately 40% of the external mechanical work performed by the RV is consequent upon left ventricular shortening. Interestingly, in their preparation, pacing of the electrically isolated RV lead to very little mechanical effect on the LV.

While the implication of this observation is that the RV has little impact on left ventricular performance in the structurally and functionally normal heart, the same cannot be said when it is affected by the disease. Brookes et al.¹¹ showed that normal left ventricular contractility is dependent on a geometrically normal myocardial mass and, in particular, on the structural and functional integrity of the RV. With biventricular conductance catheters used to assess instantaneous changes in right and left ventricular performance, acute right ventricular dilatation led to a reduction in left ventricular contractility, as assessed by end-systolic elastance and preload recruitable stroke work. While this effect was amplified by pericardial constraint, even when the pericardium was fully opened (obviating any secondary effect on left ventricular volumes), left ventricular contractility was impaired. These observations are important, as they support the rationale for an “open-chest” strategy under circumstances of postoperative RV dilation, but they also suggest other possible therapeutic avenues by which right ventricular dysfunction may be rescued, e.g., via beneficial right-left heart interactions by harnessing a left ventricular Anrep effect (increasing myocardial contractility in response to increased afterload, a phenomenon discovered by Gleb von Anrep in 1912). This is discussed below.

MANIFESTATIONS AND TREATMENT OF “ISOLATED” RIGHT VENTRICULAR SYSTOLIC DYSFUNCTION

The consequences of right ventricular systolic dysfunction in the setting of acquired heart disease, such as coronary artery disease and pulmonary hypertension, are discussed

elsewhere. Interestingly, acute right ventricular systolic dysfunction in congenital heart disease is relatively uncommon. Indeed, while maladaptive right ventricular systolic dysfunction, with RV dilatation and reduced ejection fraction, is a common manifestation of end-stage congenital heart disease, acute right ventricular dysfunction in the absence of pulmonary hypertension is relatively unusual. That said, the congenitally malformed RV is not immune to coronary ischemia (e.g., after surgery involving the right coronary artery) and can be more directly adversely affected by specific congenital heart operations (e.g., surgery for Ebstein’s anomaly of the tricuspid valve, pulmonary valve replacement, after orthotopic heart transplantation). Although the word “isolated” is used in its introduction, the preceding section exposes this characterization as flawed. While “predominant” right ventricular dysfunction is the norm under these circumstances, it is rarely truly isolated. Nonetheless, the fact that left ventricular systolic performance is often well preserved in these patients does provide some therapeutic dilemmas, as well as opportunities. The treatment algorithm of ventricular dysfunction in congenital heart disease essentially follows the same pattern as that developed for the treatment of left ventricular dysfunction in acquired heart disease. Positive-pressure ventilation, inotropes, and vasodilators all play important roles. However, under some circumstances any or all of these therapies may have adverse consequences, particularly in isolated RV disease. Indeed, given that the RV is so dependent on a low afterload for optimal function, all efforts should be made to minimize afterload. Consequently, the use of therapies that may elevate RV afterload (be it in the conduit pulmonary arteries, arteriolar resistance, left atrial pressure, or via the effect of mean airway pressure; see below) should be avoided or reversed. The natural reaction to a low-cardiac-output state (even when driven primarily by right ventricular systolic dysfunction) is to start an inotropic agent. While clearly there is a role for inotropy under such circumstances, in other situations the adverse effects of inotropic stimulation may predominate. The “mismatch” between LV and RV that sometimes occurs makes the effects of inotropic agents and vasodilators difficult to predict. Clearly, there will be little benefit, in terms of systolic performance, to an already normally functioning LV, and induction of tachycardia and a potential rise in left ventricular end-diastolic pressure in response to inotropes and a lowering of the systemic vascular resistance in response to vasodilators (if not matched by a rise in cardiac output) may all be counterproductive. Indeed, increasing left ventricular output, if not matched by a similar inotropic response on the right side, may have adverse consequences on right ventricular preload and may induce

acute right heart dilatation (and as discussed above, potentially a paradoxical worsening of LV function). For example, in a study of RV responses after brain death, this “contractility mismatch” in response to dopamine infusion was manifested as a further increase in an already increased RV end-diastolic volume in response to increased LV output,¹² suggesting that the RV is on the declining portion of its Starling curve. Furthermore, systemic vasodilation, with a fall in left ventricular developed pressure, may also have adverse consequences. While clearly a beneficial strategy when left ventricular contractile reserve is limited, reduction of afterload of a normally functioning LV may undermine some of the homeometric mechanisms that are fundamental to normal biventricular performance. As discussed briefly above, the left ventricular Anrep effect describes the circumstances where left ventricular contractility increases in response to a modest increase in left ventricular afterload. This may, in turn, be beneficial to right heart function. Given that right ventricular contractile function is partly dependent on left ventricular contractility, it may be possible to support the failing RV via induction of beneficial ventricular-ventricular interactions. This has been demonstrated in the setting of acute right heart failure induced by increased RV afterload in experimental animals.^{13,14} Presumably working via increased contractility of shared myofibers between the LV and the RV, aortic banding in these animals increases right ventricular pressure development and right ventricular stroke volume. Importantly, in one of these studies,¹⁴ right coronary flow was kept constant in order to obviate a confounding effect on coronary flow, under circumstances where ischemia may have been playing a role in the induced RV dysfunction. While the same augmentation in stroke volume with aortic banding was observed in this study, this cannot be taken to imply that coronary ischemia does not play a role in clinical RV failure and that strategies that improve right coronary artery flow may be beneficial.

With this in mind, and while clearly aortic banding is not a clinically relevant therapeutic strategy, we have recently shown that vasopressor therapy may be an alternative in these very particular circumstances of predominant right ventricular systolic dysfunction with maintained left ventricular systolic performance. Again, using animal models, we showed that systemic vasoconstriction with norepinephrine, in the setting of acute right ventricular systolic dysfunction imposed by pulmonary artery banding, increased right ventricular contractility, as assessed from right ventricular maximal elastance measured by conductance catheters, and increased right ventricular stroke vol-

ume.¹⁵ Interestingly, while we were able to recapitulate the previous findings regarding stroke volume changes with aortic banding, the reflex bradycardia that occurred with such intervention limited the changes in cardiac output. With a vasoconstrictor strategy, there was no such reflex bradycardia, and overall there was a highly significant increase in cardiac output. Thus, while counterintuitive to many therapeutic algorithms currently used in postoperative hemodynamic care support, vasoconstrictor therapy may be a rational approach to the patient with predominantly right ventricular systolic disease and well-preserved left ventricular function. It must be pointed out, however, that while anecdotally this appears to be the case for some patients, there are no clinical data to support this speculation at present.

RIGHT VENTRICULAR DIASTOLIC DYSFUNCTION

If the assessment of systolic dysfunction is difficult enough, then the assessment of diastolic dysfunction, particularly as it pertains to right ventricular performance, is potentially even more challenging. Nonetheless, it has become clear over the past 2 decades that isolated diastolic dysfunction can be a fundamental part of low-cardiac-output syndrome after surgery for some congenital heart diseases.

The reason that assessment of right ventricular diastolic function is so challenging is not only the general limitations of noninvasive assessment, for example, assessment of trans-atrioventricular valve flow, but also the fact that the RV is not a closed system in diastole. Thus, even with invasive measurements, assessment of ventricular compliance and stiffness may be invalid. The accurate assessment of diastolic compliance requires a measurement of a pressure increment and its resulting volume increment, or vice versa. As for the determination of systolic performance, insights from pressure-volume characteristics have proved crucial to the understanding of left ventricular diastolic function. Measurement of the end-diastolic pressure-volume relationship, as either a linear or an exponential function, allows us to understand myocardial compliance characteristics somewhat independent of loading conditions. This is important, as abnormal compliance may not be manifested as a raised left ventricular end-diastolic pressure when preload is reduced. Nonetheless, such measurements are valid only when the ventricle is a “closed” system, i.e., when changes in flow into the ventricle are reflected by pressures within it. The relatively high aortic diastolic pressure allows assessment of changes of left ventricular pressure in response to changes in left ventric-

ular volume in the normal LV, and the slope of the end-diastolic pressure-volume relationship is under these circumstances a valid measurement of a component of ventricular compliance.

Such boundary conditions often do not exist for the RV. The low diastolic pressure in the main pulmonary artery means that the relationship between changes in ventricular pressure and changes in ventricular volume may not be consistent. If the impedance to right ventricular filling is greater than the impedance to flow provided by the pulmonary vascular bed, then such transtricuspid flow is translated through the ventricle into the pulmonary artery (the RV acting as a “conduit” at end diastole). Consequently, right atrial contraction may not necessarily lead to an increase in right ventricular volume or be reciprocated by a change in pressure. As a result, the end-diastolic pressure-volume relationship cannot be assessed with any validity. Similarly, the validity of assessing right ventricular diastolic function from transtricuspid flow characteristics will be undermined. However, the presence of

antegrade diastolic flow in the pulmonary artery in late diastole can be a useful marker, albeit qualitative, of abnormal right ventricular compliance. Indeed, we described this characteristic of “right ventricular restrictive physiology” in patients after repair of congenital heart diseases. Most prominent after repair of tetralogy of Fallot and its closely related disorders, restrictive right ventricular physiology is characterized by a low-cardiac-output syndrome, with expected secondary effects such as impaired renal function and fluid retention.¹⁶ Figure 2 shows a typical Doppler recording in the main pulmonary artery of a patient after repair of tetralogy of Fallot, in whom there was restrictive physiology. There is an obvious biphasic pattern of antegrade pulmonary flow, there being the normal systolic flow spectral as well as a late diastolic flow spectral after the p-wave on the electrocardiogram.

While antegrade diastolic flow is a manifestation of adverse ventricular compliance, its physiologic consequences are beneficial. This is for two reasons. First, antegrade diastolic flow clearly contributes (by up to 40% or 50%¹⁵) to

Figure 2. Pulsed-wave Doppler recording of flow in the main pulmonary artery after repair of tetralogy of Fallot. There is restrictive diastolic physiology, characterized by the biphasic pattern of antegrade flow. In addition to the expected systolic flow spectral, there is antegrade diastolic flow after the p-wave on the electrocardiogram (arrows).

the overall cardiac output, and second, it limits the duration of pulmonary incompetence, which is so often present in these patients. Thus, maintenance and enhancement of antegrade diastolic flow are crucial to maintaining adequate cardiac output in these patients. From first principles, this flow is generated by a relatively small pressure transient between the right atrium and the pulmonary artery in late diastole. Simultaneous measurements suggest that this potentially large contribution to cardiac output is generated by pressure transients of just 1 or 2 mmHg (see Fig. 3). Small changes in right atrial or pulmonary artery hemodynamics can therefore have a large impact on cardiac output. Lowering the total pulmonary resistance is crucial to the management of these patients and is discussed further in “Cardiopulmonary interactions” below. Clearly, maintenance of sinus rhythm is also important in these

patients, as is maintenance of adequate right atrial preload. There is, of course, a balance to be achieved. Increasing right atrial pressure will likely increase antegrade diastolic flow and cardiac output. However, the secondary effects of frequent fluid administration cannot be ignored. The response to fluid administration is often transient and may ultimately lead to tissue edema, pleural effusions, and ascites, all of which may have adverse consequences in these patients. Similarly, the presence of a low-cardiac-output syndrome often leads to the reflex use of inotropes and inodilators. Given that biventricular systolic performance is rarely a concern, the effect of such therapies may be adverse, leading to tachycardia, vasodilation, and hypotension. One of the most effective strategies to have evolved from a better understanding of right ventricular diastolic dysfunction is the creation in infants of a patent foramen

Figure 3. Postoperative hemodynamics in a patient with restrictive right ventricle diastolic disease. There are simultaneous waveforms of the arterial blood pressure (ABP), right atrial pressure (RAP), and pulmonary artery pressure (PAP). Note how the RAP exceeds pulmonary artery diastolic pressure by 2 or 3 mmHg during the first few beats. This generates the antegrade diastolic flow demonstrated in Figure 2 and shown in the inset below the waveforms. The arrows highlight a transient reversal of gradient between the PAP and the RAP (thereby abrogating antegrade diastolic flow). This results from changes in intrathoracic pressure induced by inspiratory pressure changes from the mechanical ventilator.

ovale, if not already present.¹⁷ The physiology of a patent foramen ovale under these circumstances is now well established. Poor right ventricular compliance will lead to right-left shunting at the atrial level. While mitigating the effects of right atrial contraction on pulmonary antegrade diastolic flow, the overall potential benefit of a patent foramen ovale is large. Albeit at the expense of transient cyanosis in the postoperative period, right-left shunting can maintain left ventricular cardiac output. So long as there is an appropriately adjusted hemoglobin, the consequent benefit on oxygen delivery to tissues outweighs the impact of residual cyanosis. Consequently, the maintenance of a patent foramen ovale has become commonplace in most units performing such surgery.

The pathogenesis of restrictive physiology is related to the degree of myocardial damage imposed at the time of surgery, those with subsequent restrictive physiology having higher troponin release immediately after aortic cross-clamp removal.¹⁸ However, its early manifestations are transient. Right ventricular compliance tends to improve postoperatively over the first 48–72 hours in most cases. Consequently, low-cardiac-output syndrome, or desaturation if a patent foramen ovale is present, is usually similarly transient. Nonetheless, these patients can be exceptionally unwell, and additional methods of circulatory support may be beneficial. A readily modifiable factor that can lead to profound changes in cardiac output in these patients can be manifested as a consequence of important cardiopulmonary interactions that are discussed below.

CARDIOPULMONARY INTERACTIONS

Just as right-left interactions have proven to be integral to normal cardiovascular performance, so heart-lung interactions are similarly influential. This was demonstrated more than 50 years ago in the monumental Nobel Prize-winning experiments by André Cournand. He showed that a relatively modest increase in mean airway pressure of 5–10 cm of water (imposed by mask ventilation) led to a 10%–15% reduction in cardiac output in medical student volunteers.¹⁹ For decades this was assumed to be related to decreased systemic venous return. More recent animal experiments have cast new light on this assumption, however. Clearly, if the reduction in cardiac output associated with increased mean airway pressure is only a preload-related phenomenon, restoring preload should restore cardiac output. This hypothesis was tested by Henning²⁰ and colleagues in dogs. As expected, there was a reduction in right ventricular end-diastolic volume as mean airway pressure increased, reflecting reduced preload. However, restoring end-diastolic volume to baseline levels failed to

restore cardiac output to baseline levels. Stroke volume remained lower and end-systolic volume remained higher than baseline. The implication of this is that an increased afterload, even one as modest as a few-centimeters-of-water increment to mean airway pressure, decreases right ventricular contractile performance. Under circumstances where intrinsic right ventricular systolic performance is already compromised, one might expect these adverse cardiopulmonary interactions to be even more pronounced. Similarly, given the physiology of restrictive right ventricular disease and the dependence of cardiac output on tiny pressure transients between the right atrium and the pulmonary artery in late diastole, small changes in total pulmonary resistance, as a manifestation of changes in mean airway pressures, are likely also to impose a large impact on right ventricular output. Under these circumstances, therefore, positive-pressure ventilation may have particularly important adverse consequences.

We tested this in a series of experiments using a negative-pressure cuirasse device to mimic normal breathing, at least in terms of mean airway pressure.^{21,22} By transferring individual patients between standard positive-pressure ventilation and negative-pressure ventilation, we were able to assess the impact of intermittent positive-pressure ventilation (IPPV) on cardiac output. Our initial experiments were performed in hemodynamically “normal” children in the cardiac catheterization laboratory, e.g., those who had undergone simple interventions such as closure of a small arterial duct. These studies were therefore quite similar to the studies of normal volunteers reported by Cournand¹⁹ some 60 years earlier. Compared to cuirasse ventilation with a mean airway pressure between –3 and –5 cm of water, IPPV, with a modestly raised mean airway pressure of 6–8 cm of water, reduced the cardiac output by a little more than 10%. We then tested the hypothesis that cardiac surgery, by its effect of reducing right ventricular systolic performance, may amplify these adverse cardiopulmonary interactions. Using a similar experimental protocol, we were able to show in patients who had undergone “simple” cardiac surgery, such as atrial or ventricular septal defect closure, a much more marked impact of IPPV on cardiac output. Compared with negative-pressure ventilation, cardiac output fell by almost 30% with IPPV in such individuals. Figure 4 shows the overall results. The resting cardiac output is lower in the postoperative group, and the adverse effect of cardiopulmonary interactions imposed by IPPV, both in absolute terms and as a percentage of the cardiac output, is increased, suggesting that the clinical impact may be greater. Finally, we looked at patients after more complicated surgeries, such as tetralogy of Fallot re-

Figure 4. Comparison of the effects of negative-pressure ventilation (NPV, as a surrogate of normal breathing) and intermittent positive-pressure ventilation (IPPV) in healthy children and those after cardiac surgery. The adverse effect of IPPV is most pronounced (in both percentage and absolute terms) in children after cardiac surgery (in whom the basal cardiac output is already compromised), suggesting a greater dependency of cardiac output on cardiopulmonary interactions (see text for details).

pair and the Fontan procedure, both situations where adverse cardiopulmonary interactions may be exaggerated. Unsurprisingly, there was an even greater change in cardiac output with positive-pressure ventilation under these circumstances. Indeed, prolonged negative-pressure ventilation led to an increased cardiac output that exceeded 40% under some circumstances.²²

It is clear, therefore, that adverse cardiopulmonary interactions are particularly pronounced in patients with right heart disease and that the adverse impact of positive-pressure ventilation should be appreciated in patients on, for example, the intensive care unit. The practical implications of these data are somewhat limited, however, given that negative-pressure ventilation is not a clinically facile technique. Nonetheless, it is usually possible to minimize mean airway pressure while maintaining adequate alveolar ventilation and oxygenation, by simple modifications of standard ventilator settings. Lowering the positive end-expiratory pressure, decreasing the inspiratory time, and minimizing plateau times all may reduce mean airway pressure, with consequent benefits to cardiac output. More recently, different modes of positive-pressure ventilation have been shown to have beneficial effects. Airway pres-

sure release ventilation (APRV) is a relatively new mode of ventilation whereby intermittent reductions in a continuous airway pressure allow for alveolar ventilation at relatively low mean airway pressure. Using this technique in patients after tetralogy repair and cavopulmonary anastomoses, we were able to show that APRV during weaning from the ventilator was associated with an approximately 20% increase in cardiac output in these children.²³

CONCLUSIONS

The complexity of congenital heart disease adds to the difficulties in assessing right ventricular systolic and diastolic performance. Nonetheless, it is clear that even in the “corrected” circulation of patients with congenital heart disease, important right-left heart interactions and cardiopulmonary interactions are at play. Not only are these interactions important to recognize, as they potentially contribute to low-cardiac-output syndromes, both driven by systolic and diastolic dysfunction, but they are also potential therapeutic targets. Indeed, harnessing these interactions may have more therapeutic potential than traditional strategies of inotropes and systemic vasodilators developed for left heart disease.

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