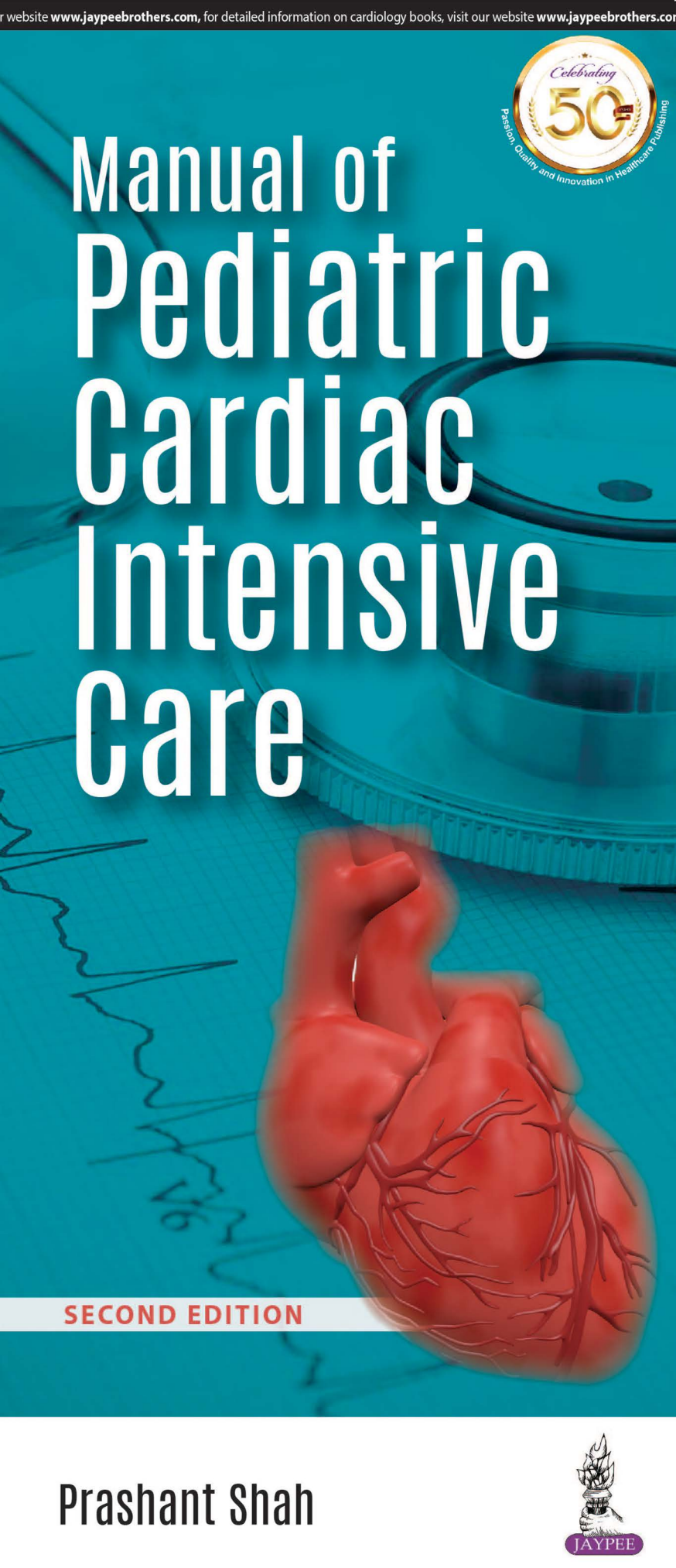
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Manual of Pediatric Cardiac Intensive Care



SECOND EDITION

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Chapter

3

Cardiovascular Function and Assessment

Suryanarayanpillai Hari Prakash, Karthik Surya

CARDIOVASCULAR MANAGEMENT

The basic concepts of cardiovascular physiology and the management of cardiovascular derangements after surgery have been elucidated. This section concentrates on the special problems encountered in pediatric patients after cardiac surgery.

SPECIAL FEATURES OF PEDIATRIC CARDIAC MANAGEMENT

- Variable pathology. The nature of the congenital heart defect, the adequacy of the palliative or corrective procedure and any residual pathophysiologic abnormalities must be taken into consideration when selecting a course of management. Some of these factors include:
  - The effects of the congenital defect on the ventricles (hypertrophy or dilatation) and on the pulmonary vascular resistance.
  - Lesions left uncorrected (valve stenosis or insufficiency, small pulmonary arteries, intracardiac shunt).
  - Surgical trauma (suboptimal myocardial protection, ventriculotomy incisions, heart block).
  - The possibility of an inadequate or disrupted surgical repair (thrombosed systemic-to-pulmonary shunts, residual intracardiac shunts, persistent valve stenosis or insufficiency after a valve repair).
- Compensatory mechanisms for impaired cardiac function are more effective in children than in adults, which may mask the extent of cardiac dysfunction. Tachycardia is one of the major compensatory mechanisms to maintain cardiac output following surgery. Significant hypovolemia and poor contractility may be present at normal blood pressure because of increased systemic resistance. Attention to signs of circulatory decompression (impaired perfusion, oliguria and acidosis) is a means of improving cardiac function because the development of hypotension is a late sign of profound decompression.

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- Monitoring limitations may also prevent the early detection of cardiovascular decompression. Invasive monitoring to measure the cardiac output directly (Swan-Ganz catheter, PA pressure line and thermistors) is cumbersome, hazardous and is generally avoided except in complex cases. Intracardiac monitoring is usually limited to right atrium (RA) and left atrium (LA) lines:
  - The RA and LA lines provide information on loading conditions of the ventricles; inferences about the status of ventricular function can be made as well, especially after serial volume challenges. Elevated filling pressures suggest the presence of ventricular dysfunction downstream to the measurement.
  - The arterial pulse pressure is the reflection of left ventricular stroke volume and should exceed 20–25 mm Hg in small children. An arterial pulse pressure of less than 15 mm Hg is a sign of low cardiac output.
  - A mixed venous oxygen intracardiac shunt reflects either anemia or a low cardiac output. The SvO_2 is ideally measured using a PA catheter, but in its absence, samples drawn from the RA or CVP line are fairly representative.

ASSESSMENT OF LOW CARDIAC OUTPUT STATES

- Owing to limited monitoring techniques, the assessment of cardiac output must involve a careful patient examination with particular attention paid to peripheral perfusion (skin, color, temperature, pedal pulse, capillary refill), and liver size (to assess RA pressure and fluid status).
- Urine output is usually a reflection of myocardial function. Evidence of oliguria (<1 mL/kg/h) in a child suggests a low output state.
- The development of metabolic acidosis is a reflection of inadequate tissue perfusion, which is irreversible spiral of cardiac decompensation and must be treated aggressively.
- Special care must be taken to normalize the core temperature so that the temperature of the extremities can be used as an index of cardiac function. Measures include use of a heated humidifier in the ventilator circuit, a heating blanket, overhead infrared warmer, and fluid and blood infusion warmers. A core temperature over 39°C reflects a high systemic vascular resistance (SVR) and inability to conduct heat.
- Clinical deterioration should prompt a repeat physical examination. For example, absence of bilateral breath sounds may indicate a pneumothorax; loss of a shunt

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murmur may explain increasing cyanosis; reappearance of a ventricular septal defect (VSD) murmur following closure may account for recurrent heart failure.

- Clinical assessment—Table 3.1 is a guide to clinical assessment of cardiac output.

CAUSES OF IMPAIRED CARDIAC PERFORMANCE

The major causes of impaired cardiac performance after open-heart surgery are:

- Hypovolemia:
  - Redistribution.
  - Blood loss.
- Capillary leak, ascites, effusions.
- Myocardial dysfunction—postoperative ischemia (X clamping).
- Residual lesions, e.g. VSD, obstructive lesions.
- Increased afterload—including pulmonary hypertension.
- Abnormalities of heart rate and rhythm:
  - Bradycardia—fixed SV.
  - Tachycardia—filling time.
- Subendocardial perfusion.

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TABLE 3.1: Clinical findings in low cardiac output state.

Category	*Parameter*	*Finding/Data*
Physical examination		
	Peripheral perfusion	Cool or mottled extremities Diminished peripheral pulses Delayed capillary refill
	Respiratory status	Tachypnea, increased work of breathing grunting flaring retractions
	Cardiac examination	S3 or S4, diminished heart tones, tachycardia or bradycardia
	Other physical examination	Diaphoresis, hepatomegaly, jugular venous distension, increasing cyanosis
	Mental status	Lethargy or irritability
Monitor data		
	Arterial waveform	Diminished pulse pressure, decreased upslope, hypotension, increased variation with respiration
	Atrial filling pressures	Significantly elevated or decreased, lack of 'a' wave

Contd...

Contd...

Category	*Parameter*	*Finding/Data*
	ECG	Nonsinus rhythm tachycardia, bradycardia, ST-segment depression or elevation, lack of HR variability
	End-tidal CO_2	Decrease in $ETCO_2$ large end-tidal to arterial CO_2 difference
	Temperature	Increased core-to-periphery temperature gradient (>5°C core to toe)
	Mixed venous (PA) or central venous (SVC) oxygen saturation	Low SvO_2 or $ScVO_2$ <50%
	Near-infrared spectroscopy regional oxygen saturation	Low cerebral rSO_2 <50%
Laboratory and radiographic date		
	Serum lactate	Increasing or persistently elevated over 2 mmol/L
	Calculated base deficit	Increasing or >5 mEq/L
	BNP	Elevated above 100 pg/mL and increasing
	Troponin-I	Elevated above 0.15 ng/mL and increasing
	Chest radiograph	Cardiomegaly, pulmonary edema or paucity of lung vascular markings
	Renal function	Elevated BUN and creatinine Poor urine output <0.5 mL/kg/hr
Echocardiography		
	LV ejection fraction or shortening fraction, dilated LV	Decreased (EF <50% or SF <35%)
Calculated cardiac index		
	Thermodilution, lithium dilution, pulse contour analysis, echocardiographic by VTI method	2.0 L/min/m^2

(S3-S4: third and fourth heart sounds; ETCO: end-eidal carbon dioxide; PA: pulmonary artery; SVC: superior vena cava; SvO: mixed venous oxygen saturation; $ScvO_2$: mixed or central venous oxygen saturation; rSO_2: regional oxygen saturation; BUN: blood urea nitrogen; EF: ejection fraction; SF: shortening fraction; VTI: velocity time integral method)

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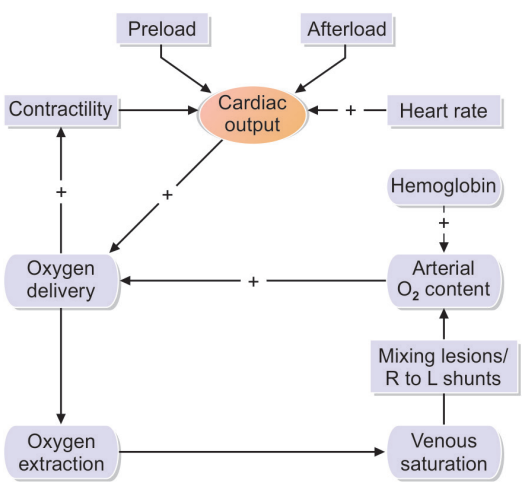
- Loss of atrial contraction (may decrease CO by 25–30% in the presence of poor LV function).
- Acidosis:
  - Metabolic—tissue hypoperfusion.
  - Respiratory—hypoventilation.
- Electrolyte disturbances—low ionized calcium.
- Cardiac tamponade.

LOW CARDIAC OUTPUT

The assessment of low cardiac output states in infants and children requires the integration of clinical and monitoring techniques. In general, children compensate well for a low cardiac output by peripheral vasoconstriction and tachycardia such that a fall in arterial blood pressure is a late sign of cardiac decompression (Flowchart 3.1).

- Diagnosis:
  - Suspicion of low cardiac output is raised by evidence of peripheral vasoconstriction (cool, pale extremities, mottling, absent pedal pulses and capillary refill exceeding 3s), oliguria, metabolic acidosis and hyperthermia.
  - Increased lactate level on arterial blood gas.
  - Temperature gradient of more than 4–5° between the peripheral and core (rectum) temperature.
  - A narrow arterial pulse pressure, elevated filling pressures, low RA oxygen saturations and the development of atrial or ventricular arrhythmias also draw attention to a low cardiac output state.
- Treatment:
  - The treatment of a low cardiac output syndrome requires the assessment and manipulation of heart rate and rhythm, volume status, contractility and

Flowchart 3.1: Determinants of cardiac output and oxygen.



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afterload. Each of these factors is discussed in the subsequent sections.

Additional contributory factors to a low cardiac output should be identified and treated. These may include:

- Cardiac tamponade (assessed by echocardiography).
- Ventilatory problems (chest X-ray to rule out severe pulmonary vascular congestion, atelectasis, pneumothorax, or large hemothorax; ABG's to identify hypoxia or hypercarbia).
- Metabolic problems (acidosis, hypo- or hyperkalemia, hypocalcemia).

HEART RATE AND RHYTHM

- If possible, the heart rate and rhythm should be optimized to achieve a regular supraventricular rhythm. The optimal heart rate is determined by the child's age (Table 3.2); the actual pulse rate will usually exceed the resting baseline values because of increased levels of circulating catecholamines and the use of inotropic drugs following surgery. Tachycardia is the most significant compensatory mechanism in children to maintain cardiac output, and may simply reflect hypovolemia that should be treated simultaneously.
- Sinus and nodal bradycardia should be treated with atrial pacing.
- Complete heart block, which may occur after operations requiring suturing near the AV node (VSD, AV canal), should be treated with AV sequential pacing. It is important to take advantage of the atrial contribution to filling in the early postoperative period.

TABLE 3.2: Average heart rates in children.

Age	*Average heart rate*	
	Mean	*Range*
Newborn	123	94–154
1–2 days	123	91–159
3–6 days	129	91–166
1–3 weeks	148	107–182
1–2 months	149	121–179
3–5 months	141	106–186
6–11 months	134	109–169
1–2 years	119	89–151
3–4 years	108	73–137
5–7 years	100	65–130
8–11 years	91	62–130
12–15 years	85	60–119

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- Supraventricular tachyarrhythmias are more difficult to treat, but usually respond to digoxin, type IA antiarrhythmics, or electrical cardioversion, if necessary.
- Junctional ectopic tachycardia (JET), a potentially fatal arrhythmia, should treat aggressively (*see* Chapter 9: Cardiac Arrhythmias).

ACCEPTABLE PARAMETERS

Because each child's postoperative cardiac status is unique, initial acceptable parameters for blood pressure, RA and LA pressures, and urine output should be defined by the surgeon or cardiac anesthesiologist for the house staff and nurses at the time the patient arrives in the ICU. In the postoperative patient, there is a variation from normal baseline values for the resting child. Furthermore, there is frequently a change in myocardial performance and peripheral vasomotor tone during the early postoperative period that will require a redefinition of acceptable parameters.

- Systolic blood pressures for children of various ages are listed in Table 3.3.
- The usual range of postoperative RA and LA pressure is 8–12 mm Hg.

However, higher pressures are commonly required to optimize cardiac performance and depend on the specific cardiac lesion and the operative procedure.

- Urine output should exceed 1 mL/kg/h.
- *Special studies:* When cardiac performance following corrective surgery is not as expected and does not respond to standard therapeutic measures, early reinvestigation is recommended:
  - Unsuspected pericardial tamponade, ventricular dysfunction, inadequate or disrupted intracardiac repairs, or malfunctioning, prosthetic heart valves may be detected by echocardiography.
  - The intracardiac lines placed during surgery can be used to provide information on pressures, gradients and shunts.

TABLE 3.3: Normal blood pressure for various ages.

Ages	*Mean systolic ± 2 SD*	*Mean diastolic ± 2 SD*
Newborn	80 ± 16	46 ± 16
6 months–1 year	90 ± 25	50 ± 20
1–4 years	95 ± 25	65 ± 25
4–5 years	100 ± 20	65 ± 15
6–10 years	105 ± 15	57 ± 8
10–16 years	115 ± 19	60 ± 8

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- The ratio of pulmonary blood flow to systemic blood flow (Qp/Qs) is calculated using the following formula:

$$(Qp/Qs) = \frac{\text{Aortic } O_2 \text{ sat} - \text{RA } O_2 \text{ sat}}{\text{LA } O_2 \text{ sat} - \text{PA } O_2 \text{ sat}}$$

- A shunt exceeding 2:1 usually requires reoperation, whereas one that is less than 1.5:1 is not hemodynamically significant. Shunts between 1.5:1 and 2:1 require further delineation of cardiac abnormalities and a careful assessment of the patient's clinical status.
- Cardiac catheterization may be required to define residual intracardiac lesions, such as a left-to-right shunt, and early diagnosis of treatable intracardiac pathology will allow reoperation before irreversible cardiac, pulmonary, renal neurologic and/or metabolic damage has developed.

VOLUME STATUS

- The optimal preload conditions for an individual patient depend on the specific congenital defect, the nature and adequacy of the repair, and the severity of right or left ventricular dysfunction. It is important to document the filling pressures (RA and LA pressures) both at the time of weaning from cardiopulmonary bypass (CPB) and on arrival in the ICU:
  - It is common to find that higher filling pressures are required 3–6 hours postoperatively, which corresponds to the time of maximal myocardial edema and dysfunction.
  - An acute change in filling pressures may result from a change in cardiac rhythm.
  - In neonates and infants, the anterior fontanelle can be assessed for volume status.
- When there is evidence of a low cardiac output syndrome, the volume status should be addressed while potential contributing causes are being evaluated. With hypovolemia, the LA pressure will be low (<10 mm Hg) and the arterial pressure tracing will display a narrow waveform reflective of a diminished stroke volume:
  - In addition, the normal respiratory variation in blood pressure noted during positive pressure ventilation will be exaggerated on the arterial display monitor.
  - Careful assessment of the input and output, with particular attention to urine output and chest tube drainage, is also helpful in assessing the degree of hypovolemia.
- In the absence of an LA line, a low CVP is consistent with hypovolemia. However, a high CVP may indicate right

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ventricle (RV) dysfunction and/or elevated PVR. In either situation, volume infusion to normalize or increase the CVP may be required to ensure adequate left-sided filling.

- Hypovolemia should be treated with fluid replacement to expand the intravascular volume. Most centers use either blood or colloid (fresh frozen plasma or 5% albumin) as fluid boluses to maintain adequate preload. The selection of the particular fluid depends on the patient's hematocrit, clotting status and interval since surgery. Fluids are given in 5–10 mL/kg increments (6 to 12% of blood volume). Further volume infusion should be based on the hemodynamic response to each fluid bolus. An adequate response should be a rise in filling pressure and blood pressure with a decrease in heart rate and improvement in peripheral perfusion.

CARDIAC CONTRACTILITY AND AFTERLOAD

When systemic arterial hypotension or signs of low cardiac output persist after restoration of blood volume, then cardiac contractility and/or afterload require manipulation. These two factors must be considered together because of their intrinsic relationship and because most of the relevant pharmacologic agents affect both simultaneously. Almost all patients undergoing open-heart surgery for congenital heart disease will require some form of inotropic therapy to be weaned from CPB, and these medications are usually continued during the early postoperative period.

LEFT VENTRICLE AND SYSTEMIC VASCULAR RESISTANCE

- If a cardiac output persists after the LA pressure has been raised to 12–15 mm Hg by volume infusion, cardiac contractility is most likely impaired. Further volume infusion to an LA pressure of 15–18 mm Hg may be necessary to obtain more LV output by the starling mechanism.
- If high filling pressures are required, an inotropic drug with predominant β_1 activity should be administered. If the SVR is high, vasodilating agents are administered and the doses for pediatric patients are noted *(see* Appendix 1).
  - Dopamine increases contractility and heart rate and can be used up to 20 μg/kg/min without compromising renal perfusion.
  - Dobutamine improves contractility and increases heart rate, with less vasoconstrictive effects than dopamine.
  - When profound LV failure is present, milrinone is very helpful. Its combined inotrope and vasodilating

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properties enhance both RV and LV output. They are therefore beneficial in patients with either AV valve regurgitation or pulmonary hypertension.
  - Epinephrine in low doses (0.01–0.1 μg/kg/min) is a strong inotrope and chronotrope that is commonly used in neonates undergoing complicated cardiac repairs.

(For dose and infusion, kindly *see* Appendix 1).

- Contractility refers to the intrinsic strength of myocardial contraction. In congenital heart disease, it is more common to see impairment of RV function, primarily because of preexisting pulmonary hypertension of volume overload.
- Afterload refers to ventricular wall tension during systole:
  - LV function may be improved by a reduction in LA pressure and SVR. This is beneficial in patients with systemic hypertension or residual AV valve regurgitation.
  - RV function may be improved by a reduction in RV volume and PVR. This is particularly important in neonates and young infants in whom reduction in PVR is essential to maintain RV performance:
    - Isoproterenol produces primarily an increase in heart rate, but also improves contractility and reduces PVR. Therefore, it is most beneficial for children with RV dysfunction. The tachycardia is well tolerated and often beneficial in small children.
    - For cardiac failure unresponsive to drug management, intra-aortic balloon counter pulsation can be considered in the older pediatric patient.
    - For large children or adolescents, an LV assist device may be used. Extracorporeal membrane oxygenation (ECMO) can be used for cardiopulmonary failure after bypass.

RIGHT VENTRICLE AND PULMONARY HYPERTENSION

- One of the significant differences between adult and pediatric cardiac surgical patients is the common occurrence of reactive pulmonary hypertension in children, which may predispose them to episodes of oxygen desaturation and RV failure:
  - Elevated PVR, whether fixed or dynamic, is often noted in patients with large left-to-right shunts and increased pulmonary blood flow. Coexisting high PVR and an impaired RV is a very dangerous combination. The contribution of an elevated PVR to RV failure is difficult to ascertain unless PA pressures and

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cardiac outputs can be determined. Nonetheless, the treatment of RV dysfunction usually includes efforts to dilate the pulmonary vascular bed.

- The RV may also be predisposed to postoperative failure as a consequence of:
  - Underdevelopment.
  - Chronic high-pressure loading (hypertrophy).
  - Less-effective intraoperative myocardial protection.
  - Right ventriculotomy incisions.
  - Interruption of right coronary artery branches.
  - Residual pulmonary stenosis or insufficiency or tricuspid insufficiency.

- The assessment of RV function depends on clinical signs as well as a comparison of RA and LA pressure measurements. Clinically signs of RV failure include:
  - Jugular venous distension.
  - Hepatomegaly.
  - Peripheral edema.
  - Ascites.
  - Periorbital, flank and eventually generalized edema.
  - Rising blood urea nitrogen (BUN).

An elevated RA pressure with low LA pressure confirms the diagnosis of RV dysfunction. Volume loading to improve cardiac output will raise the RA pressure with proportionately less effect on the LA pressure.

- Treatment of RV failure:
  - Volume loading, often to an RA pressure of 15 mm Hg or greater, may be necessary to ensure adequate left-sided filling.
  - Use of an inotropic agent that may also produce pulmonary vasodilation should be selected. These include the following:
    - Low-dose dopamine/dobutamine.
    - Milrinone.
    - Sequential pacing if not in sinus rhythm.
    - Right ventricular assist device for older children.

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He has operated patients from more than 9 countries and has special interest in neonatal cardiac and valve repair surgeries. He has strong academic interest and has publication in national and international journals. Dr Shah is a well-known and followed by pediatric cardiac surgeons throughout the world, and he has been awarded for 'Distinguished service' October 2018.

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