General Principles of Anaesthesia for Adult Cardiac Surgery

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Intraoperative Management

The intraoperative management has a major impact on the perioperative course of patients undergoing cardiac surgery. Although a proficient surgical technique and a short surgical time are a relevant component of an uneventful course, an adequate preoperative assessment, a skillful anesthetic technique, and meticulous intraoperative monitoring, are all necessary measures to avoid potentially fatal complications.

Preoperative Counselling

The intraoperative management of patients undergoing cardiac surgery starts before the operating theatre with a preoperative counselling (Table 1).

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Table 1 Preoperative counselling

History	
Cardiac symptoms, significant comorbidities, previous anesthetic experiences, surgical procedures, allergies, medications and recent use of steroids	
Medical therapy	
Antihypertensive and antianginal medications	Continue up to and including the morning of surgery
Angiotensin-converting enzyme (ACE) inhibitors and angiotensin receptor blockers (ARBs)	Stop (eg the morning of surgery) to reduce the risk of low systemic resistance in the perioperative period
Insulin or oral hypoglycemic medications	Stop the morning of surgery. Check frequently blood glucose during surgery
Warfarin	Stop at least 4 days before surgery to have INR normalized before surgery
Aspirin (little impact on perioperative bleeding)	• In elective CABG or valvular surgery without coronary disease Stop 3–5 days before surgery • In symptomatic coronary patients Continue
Clopidogrel and prasugrel	• Stop 5–7 days before elective surgery • Continue or stop for a shorter period of time in patients with recently placed drug-eluting stents
Unfractionated heparin	• stop about 4 hours before surgery • continue into the operating room for patients with critical coronary disease
Low molecular-weight heparin	• Last dose should be given 18–24 hours before surgery • Fondaparinux stop at least 48 hours before surgery
IIb/IIIa Inhibitors (Eptifibatide and Tirofiban)	Stop at least 4 hours prior to surgery

Premedication

Premedication decreases the sympathetic tone and usually induces vasodilatation and bradycardia which may lead to cardiogenic shock in poorly compensated patients (e.g. critical aortic stenosis, congestive heart failure). In these patients premedication, should be given with caution due to the risk of cardiocirculatory collapse (Table 2).

The prophylactic antibiotics (usually a cephalosporin) must be administered within 1 hour of skin incision. In patients allergic to β-lactam, vancomycin giving in 1 h is the antibiotic of choice.

Table 2 Anesthetic premedication for cardiac surgical patients

• Temazepam 10–20 mg or diazepam 5 mg P.O the night before surgery
• Midazolam 1–4 mg IV or fentanyl 50–100 μg IV under monitoring

Monitoring

Before anesthesia induction, a peripheral venous access and a full monitoring are required. A 5-leads electrocardiography (E.C.G) with a continuous visualization through DII and V5 leads, an arterial line usually placed in the radial artery for invasive blood pressure, pulse oximetry, urinary Foley catheter for urine output, and core body temperature are the standards for basic Anesthetic monitoring in cardiac surgery it is common practice to defer central lines placement after anesthetic induction to avoid discomfort and anxiety in awake patients. In fact, tachycardia and hypertension increase myocardial oxygen consumption. Only in patients with low cardiac output (CO) or hemodynamic instability would need a pre-induction central line placement to start vasoactive drugs.

Cannulation of the right or alternatively left jugular vein under ultrasound guidance is achieved with a 7 Fr 3 lines catheter to measure central venous pressure (CVP) and in some hospitals with a 8.5 F pulmonary artery catheter (PAC) introducer. Usually, PAC is placed after the induction only in high risk patients with pulmonary hypertension, low ejection fraction or when a difficult weaning from the CPB is anticipated. Possible complications associated with PAC are summarized in the Table 3. There is no evidence showing that the routine use of PAC improve outcomes. However, data from observational cohorts in selected high-risk patients show that might be of benefit. Literature shows that TEE is a cost-effective tool impacting the surgical planning. The probe is inserted before heparinization and after intubation. It provides information on ventricular function, valve pathology or intracardiac masses by Bright mode, 3D, M-Mode, flow Doppler (continuous, pulse, color and tissue) (Table 4). TEE has few contraindications and in less than 0.1% of cases it is associated with severe complications (Table 5).

General Anesthetic Considerations

Cardiac surgery patients are fragile, and no single protocol can guarantee hemodynamic stability during induction. Hemodynamic changes depends on patient's pathophysiology and on the administered pharmacological agents. A reduction in sympathetic tone, due to inhalation and I.V agents is associated with vasodilatation, cardiac depression, and relative hypovolemia, which acting together may lead to hypotension and cardiogenic shock if not promptly treated. Thus, the use of small dose of vasoconstrictor for induction (e.g. etilefrine 1–4 mg iv), in rapid succession

Table 3 Complications associated with pulmonary artery catheter

During positioning	Post positioning
• Arterial puncture	• Thrombosis and venous embolism
• Tricuspid valve traumatism	• Infections—Endocarditis
• Arrhythmias	• Transient Right Bundle Branch Block
• Pulmonary artery disruption	
• Mechanical damage to cardiac structures	

Table 4 Role of transesophageal echocardiography

Before surgery	During surgery	Post surgery
Confirming diagnosis and feasibility of surgical correction	Modifying and targeting anesthetic management	Evaluation of RV/LV systolic and diastolic function
Helping in choice of surgical technique correction	Check placement of CPB cannulas	Verification of surgical correction
	Weaning from CPB	Detection of regional wall motion abnormalities
	De-airing after CPB	
	Check for IABP position	

CPB: cardiopulmonary bypass; IABP: Intra-aortic balloon pump

Table 5 Complication and contraindications of transesophageal echocardiography

Complication of TEE	Contraindications of TEE
Esophageal rupture/perforation	Esophageal pathologies
Upper GI bleeding	Large diverticulum
Laryngospasm or bronchospasm	Obstruction, stricture
Arrhythmias	Recent upper GI bleeding

TEE: transesophageal echocardiography; GI: gastrointestinal

after the administration of sedative drugs may be useful in preventing the "lethal triade" hypotension, ischemia and ventricular fibrillation.

The following cardiovascular medications should be available before induction:

a. Atropine (bolus)
b. Epinephrine (bolus or continuous infusion)
c. Calcium chloride (bolus)
d. Ephedrine or Etilefrine (bolus)
e. Lidocaine (bolus)

Laryngoscopy can lead to hypertension and cardiac decompensation and opioids do attenuate the hemodynamic response. The administration of IV lidocaine 1.5 mg/kg 1–3 min before laryngoscopy is also effective in blunting the sympathetic effected triggered by direct laryngoscopy (and can also reduce propofol-related pain). However, given its vasodilatation and myocardial depression effects, it is not recommended in patients with moderate to severe LV impairment or severe aortic stenosis. Recommended anesthesia induction doses are shown in Table 6.

Since almost all fasted patients are are associated with relative hypovolemia, a careful augmentation of the intravascular volume in the preinduction period with crystalloids may be useful. It is important to avoid overload and hemodilution especially in patients with congestive heart failure. A precocious initiation of inotropes in patients with low cardiac index sometimes helps to maintain a stable perfusion pressure and cardiac output during the preinduction period. In Table 7, an hemodynamic responses to surgical stimuli is shown.

Precardiopulmonary Bypass Period

In patients undergoing cardiac surgery, even if an intraoperative anesthetic regimen including volatile agents is associated with a reduced postoperative cardiac dysfunction when compared to a total intravenous drug anesthesia, no differences in postoperative and long term survival are detectable. During the pre-CPB period the maintenance of a sufficient myocardial oxygen supply/consumption can be achieved with an adequate analgesia plan and administration of short-acting agents to manage blood pressure (norepinephrine as vasoconstrictor and nitroglycerine as vasodilator) is seldom required (Fig. 1). Monitoring anesthesia depth should be

Table 6 Suggested anesthesia induction doses

Hypnotics	
Propofol	1–2 mg/kg or
Thiopental	2–4 mg/kg or
Etomidate	0.15–0.3 mg/kg or
Ketamine	0.5–1.5 mg/kg
Opioids	
Fentanyl	3–10 μg/kg or
Sufentanyl	0.1–1 μg/kg or
Remifentanyl	0.1–0.75 μg/kg/min
Muscle relaxants	
Cisatracurium	70–100 μg/kg or
Rocuronium	0.3–1.2 mg/kg or
Succinylcoline	1–2 mg/kg

Table 7 Hemodynamic responses to surgical stimuli

	Pre-incision	Incision	Sternotomy	Cannulation
Surgical stimulation	↓	↑	↑↑	↓
Heart rate	↓↓	= or ↑	↑↑	= or ↓
Blood pressure	↓↓	↑	↑↑↑	↑ or ↓
Preload	= or ↓	= or ↑	= or ↑	↓
Afterload	= or ↓	↑↑	↑↑	= or ↓
O_2 Myocardial demand	↓	= or ↑	↑↑↑	↓

encouraged as it allows to avoid over sedation, hypotension and burst suppression, associated with the excess of hypnotic drugs.

Dysrhythmias are associated with intraoperative ischemia and it is therefore very important to preserve the sinus rhythm when present or to guarantee at least rate control with short-acting β-blockers (esmolol or landiolol). Consider to place sticky patches on the chest in case arrhythmias occur (atrial fibrilation, ventricular tachicardia, etc).

Specific Anesthetic Considerations

Different cardiac procedures requires specific considerations during the pre-bypass time.

Coronary Artery Bypass Grafting

Since patients undergoing coronary artery bypass grafting (CABG) have a low coronary reserve, tachycardia, hypertension and hypotension may lead to ischemia before the CPB institution. Patients with coronary disease are more vulnerable to the increase of myocardial oxygen consumption due to inability to increase

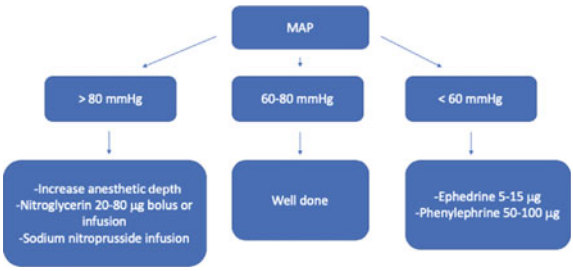

Fig. 1 Management of intraoperative blood pressure before cardiopulmonary bypass. MAP: mean arterial pressure

coronary reserve flow. In light of this, anemia should also be carefully avoided. ECG (ST alteration) and TEE (new regional wall motion abnormalities, alteration of the diastolic function) allow a prompt detection of ongoing ischemia.

Nitroglycerin, α agents vasopressors, short acting β-blockers should be considered in the event of hypertension, hypotension or to improve the consumption/delivery oxygen ratio respectively. If not sufficient, early CPB institution is required.

In off pump CABG the surgical manipulation of the heart can be associated with hypotension and suboptimal hemodynamics. Trendelemburg position, careful fluid expansion, use of α-agent vasopressors, inotropes or intraortic balloon pump should be considered on the base of blood pressure and cardiac function. A switch to CPB without aortic crossclamp (beating heart) or with aortic clamp is required in the event of persistent hemodynamic instability. Normothermia with warming systems is recommended to avoid arrhythmias.

Aortic Stenosis

Anesthesia induction of aortic stenosis patients is at high risk of complication and suggestions for the management of this period are reported in Table 8. It is crucial to avoid atrial fibrillation before CPB as it is associated with hypotension. Prompt electrical cardioversion is usually needed.

Transcatheter Valve Implantation

Transcatheter valve implantation, usually performed in sedation and local anesthesia, is an alternative to standard open cardiac surgery in selected patients with aortic stenosis at high or intermedium risk.

Nevertheless, in order to prevent malposition and embolization of the prosthesis during aortic valve ballooning and balloon prosthesis implantation, a transient partial cardiac standstill, avoiding pulsatility, and usually targeting a systolic BP below 60 mmHg, is induced by rapid pacing.

Table 8 Hemodynamic management goals in aortic stenosis

	Pre-load	Heart Rate	Contractility	SVR	PVR	Drugs to avoid
AS	LV↑	↓ (SR)	Keep normal	↑	Keep normal	Artero/venodilators β-blockers

AS: aortic stenosis; LV: left ventricle; SR: sinus rhythm; SVR: systemic vascular resistance; PVR: pulmonary vascular resistance

Aortic Regurgitation

The hemodynamic management for aortic regurgitation is summarized in Table 9.

Obstructive Hypertrophic Cardiomyopathy

Patients with obstructive hypertrophic cardiomyopathy are at risk of hemodynamic instability in the pre-CPB period. Hypovolemia or a drop in afterload may increase LV outflow tract (LVOT) gradient and trigger the systolic anterior motion. Fluid therapy, alfa 1- agonists and B-blockers may mitigate or revert the hemodynamic impairment. On the contrary, inotropes and inodilators should be avoided since they increase gradient and left ventricle (LV) obstruction.

Mitral Valve

The measures able to guarantee a good hemodynamic profile for mitral regurgitation (MR) are reported in Table 10.

Intraoperative TEE is particular useful in describing mitral anatomy and can significantly affect the surgical plan.

Percutaneous mitral repair with MITRACLIP allows treating patients with MR and at prohibitive perioperative risk. The procedure requires general anesthesia and a continuous TEE monitoring.

Mitral Stenosis

Patients with mitral stenosis should be treated following the criteria reported in Table 11.

In patients with high pulmonary pressure and/or right ventricular impairment, the insertion of PAC is recommended. Particular caution should be paid in minimising

Table 9 Hemodynamic management goals in aortic regurgitation

	Pre-load	Heart rate	Contractility	SVR	PVR	Avoid
AR	LV↑	↑	Normal or ↑ (in case of ↓ EF use inodilators)	↓	Normal	Venodilators

AR: aortic regurgitation; LV: left ventricle; EF: ejection fraction; SVR: systemic vascular resistance; PVR: pulmonary vascular resistance

Table 10 Hemodynamic management goals in mitral regurgitation

	Pre-load	Heart rate	Contractility	SVR	PVR	Avoid
MR	LV↑ (risk of augmentation MR due to annular dilatation) or ↓	↑ (Frequently AF)	Normal or ↑ (inotropes in case of ↓EF)	↓	↓	Vasopressors increasing LV afterload with caution. Hypoxia, hypercapnia, acidosis ↑ sPAP

MR: mitral regurgitation; LV: left ventricle; AF: atrial fibrillation; sPAP systolic pulmonary artery pressure; SVR: systemic vascular resistance; PVR: pulmonary vascular resistance

the number of inflations of the PAC balloon, to get the pulmonary wedge pressure. To inflate only when is needed (if low CO syndrome) and not routinely, in order to minimise the risk of PA rupture.

Tricuspid Valve Surgery

The induction of patients with tricuspid stenosis or regurgitation requires a manipulation of the pre-load, afterload and contractility as reported in Table 12. In this setting, the estimation of the CO with thermodilution is not reliable. On the contrary, echocardiography and arterial pulse wave contour analysis are more effective in the assessment of the forward stroke volume.

The correction of tricuspid regurgitation may lead, in RV dysfunction due to an increase of RV strokework. A prompt support with inotropes, vasopressors, agents able to decrease the pulmonary vascular resistances (nitric oxide), and mechanical circulatory supports is recommended.

Tricuspid diseases, increasing the central venous pressure, may affect hepatic and renal function. Thus, a subclinical coagulopathy may further worsen the effect of CPB on the coagulation system.

Table 11 Hemodynamic management goals in mitral stenosis

	Pre-load	Heart rate	Contractility	SVR	PVR	Avoid
MS	LV↑	↓	Keep normal	Normal	↓	Hypoxia, hypercapnia, acidosis ↑ sPAP

MS: mitral stenosis; LV: left ventricle; sPAP: systolic pulmonary artery pressure; SVR: systemic vascular resistance; PVR: pulmonary vascular resistance

Table 12 Hemodynamic management goals in tricuspid regurgitation

	Pre-load	Heart rate	Contractility	SVR	PVR	Avoid
TR	RV↑	Normal or ↑	Keep normal	Normal	↓	Pulmonary hypertension

TR: tricuspid regurgitation; RV: right ventricle; SR: sinus rhythm; SVR: systemic vascular resistance; PVR: pulmonary vascular resistance

Aortic Aneurysm

Ascending aortic aneurysms are usually treated surgically with CPB and aortic cross clamping. When the aortic arch is involved, a deep hypothermic circulatory arrest is necessary. If a selective perfusion of the supra-aortic vessels is required anterogradely (Kazui) or retrogradely, target temperature ranges between 24–28 °C. Without supra-aortic perfusion, a temperature of 18–20 °C allows a period of no flow of 45 min minimizing the risk of neurological injury.

Right and left radial artery, EEG/NIRS, BIS, and core temperature monitoring are mandatory during surgery involving the aortic arch. For cerebral protection, head wrapping with ice (regional cooling), methylprednisolone (30 mg/kg), thiopental or pentobarbital (5–10 mg/kg) may be considered, although there are no clear evidences.

Aortic Dissection

Since dissection requires emergency surgery, a rapid sequence induction should be applied to minimize the risk of gastric aspiration when the stomach is full. Moreover, hypertension must be treated aggressively with short term β-blocker or nitroprussiate/nitroglycerin.

TEE gives invaluable information on intimal tear, extent of dissection, degree of aortic regurgitation, involvement of the aortic root, presence of a hemopericardium and regional wall motion abnormalities secondary to the involvement of coronary arteries from the dissection, and hemothorax.

Preparation for Cardiopulmonary Bypass (CPB)

Unfractionated heparin (300 units/kg) administered directly into a central vein is the preferred anticoagulation agent for CPB. An activated clotting time (ACT) of at least 300 s is safe for cannulation, and > 480 s for CPB institution. In patients with heparin induced thrombocytopenia (HIT) bivalirudin (a thrombin direct inhibitor) is used (Table 13).

Table 13 Bivalirudin

Half time life: 25–30 min
Metabolism: 20% renal + proteolysis
Posology: 1 mg/Kg
Infusion during CPB: 2,5 mg/kg/h and up to 0,25 mg/kg/h
Stop 30 min before cardiopulmonary bypass weaning

Cannulation

CPB provides oxygenated systemic non pulsatile blood flow to organs when the heart and the lung are not functioning. With standard cannulation, an aortic cannula is positioned in the ascending aorta and a venous cannula in the right atrium (atrial cannulation) or in the superior and inferior vena cava (bicaval cannulation). In some circumstances (i.e. Type A aortic dissection), the axillary artery is the site of choice for arterial cannulation. A peripheral cannulation with the arterial and venous cannulae positioned in the femoral artery and vein may be required during some cardiac surgeries (i.e. mitral valve surgery through mini-thoracothomy, aortic valve replacement through mini-sternotomy and selected high-risk redo surgeries). During arterial cannulation a systolic blood pressure lower than 90 mmHg reduces the risk of aortic dissection.

Cardiopulmonary Bypass Period

Since the majority of CPB machines provides non pulsatile flow, mean arterial pressure (MAP) is used in order to guide the hemodynamic status (target 50–70 mmHg), combined with monitoring of urine output and lactate through seriate blood gasses analysis.

The use of CPB inevitably leads to an high degree of hemodilution owing to the use of a non-sanguineous prime. A hemoglobin value below 6.5–7 g/dl (Hct 22–24%) is usually enough to avoid oxygen delivery impairment (Table 14).

The route of anesthesia administration in cardiac surgery deserves some considerations:

1. In the event of bicaval cannulation total endovenous anesthesia must be provided in a peripheral vein because the heart is bypassed and the drugs administered in the central line can be lost in the surgical field.
2. In the pre CPB period, if the anesthesia is maintained with a volatile agent, the halogenated is usually suspended and replaced by an infusion of intravenous anesthetic (e.g. propofol) as soon as the CPB is started and the ventilator is stopped.
3. When propofol is used, an infusion rate of 3 to 6 mg/kg/h or a target plasma concentration of 2–4 μg/ml is usually enough. In fact, anesthetic requirement falls with temperature drops and hemodilution. The opposite happens during rewarming.

Table 14 On pump targets

Systemic flow rates	• 2–2,5 L/min/m2 at 37 °C • 1.8–2.5 at 30 °C
Systemic blood pressure	50–80 mmHg[a]
Arterial blood gases	PO_2 > 250 mmHg; PCO_2 35–45 mmHg; pH 7.40 and avoidance of hyperchloraemic acidosis
ACT	>480 s (can be less if heparin coated circuit)
SvO_2	>65%
Hematocrit	>22%

ACT: activated clotting time; SvO_2: mixed venous oxygen blood saturation; PO_2: pressure of oxygen; PCO_2: pressure of carbon dioxide

[a]Recently a cerebral autoregulation monitoring has been advocated to set the best MAP during CPB (J Thorac Cardiovasc Surg 2017;154:1590–8)

Cardiopulmonary Bypass Weaning

Before starting CPB weaning, heart de-airing is crucial through venting the aortic root and right superior pulmonary vein prior to cross-clamp release. Manually inflating the lungs for few seconds allows to fill in the left ventricle facilitating the de-airing process (Valsalva maneuver). TEE helps to detect residual air. The criteria to start the weaning from CPB are summarized in Table 15.

CPB weaning is the progressive reduction of the venous return from the extra-corporeal circulation to a spontaneous and normal mechanical heart activity. This process is considered completed after the administration of protamine and the removal of the venous and arterial cannulae.

TEE is crucial in promptly checking ventricles' preload and contractility, detecting overdistension and dysfunction.

CPB flow is progressively reduced (500 ml per time) until the systemic circulation is totally sustained from the heart. A flow chart on the hemodynamic management during CPB is reported in Fig. 2.

In a variable percentage of cases (10–45%), the CPB discontinuation can be complicated. Although there are no specific criteria to define the "difficult-to-wean" patient, this is a life-threatening complication associated with high perioperative mortality.
In normovolemic conditions and in absence of structural or dynamic abnormalities, difficulties CPB weaning may depend on:

a. Vasoplegic syndrome (characterized by normal or elevated cardiac output with preserved ventricular function and low systemic vascular resistance) treated with vasoactive drugs (e.g. norepinephrine, phenylephrine, vasopressin). If vasoplegia is refractory refer to Table 16.
b. Right ventricular dysfunction, with or without pulmonary hypertension. The performance of the RV depends on preload, afterload and contractility.

Table 15 Checklist before CPB weaning

Temperature	Rectal/Bladder Temperature >35 °C
Rhythm	Spontaneous or paced (HR >70 bpm) Quick possible defibrillation (10–20 J)
Ventilation	Lung re-ventilation and recruitment
TEE	TEE examination under partial cardiopulmonary bypass to detect functional or structural defects
Homeostasis	pH correction: aim 7.35–7.45 Hct > 25% Normoglycemia Potassium plasma concentration control
Surgeon	De-airing cardiac cavities Aortic unclamping

FiO_2: fraction of inspired oxygen; TEE: transesophageal echocardiography; Hct: hematocrit

c. LV systolic dysfunction, characterized by left ventricle depressed contractility. Ventricular function is a major determinant of cardiac output. Global or regional dysfunction may develop after the weaning period from CPB.
d. LV diastolic dysfunction, with impairment in ventricular diastolic relaxation and restrictive filling pattern.

Flow chart of difficult CPB weaning and TEE-guided therapeutic approach is shown in Fig. 3.

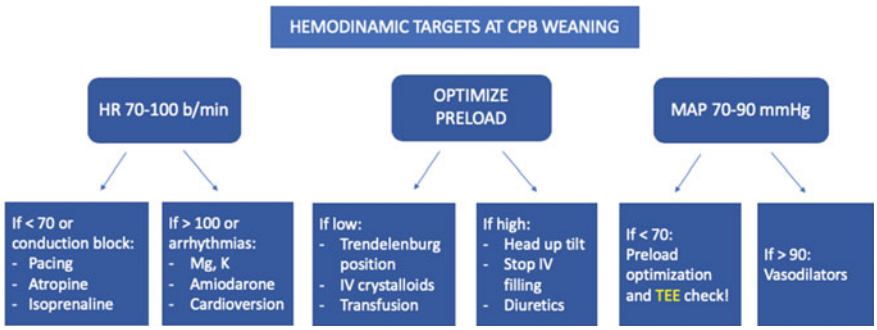

Fig. 2 Hemodynamic targets at cardiopulmonary bypass weaning. HR heart rate; MAP mean arterial pressure, Mg magnesium, K potassium, IV intravenous, TEE transesophageal echocardiograpy

Table 16 Treatment of refractory vasoplegia

First line	Transfusion (Hb target: 9 g/dL) Epinephrine infusion Steroids Diphenhydramine
Second line	If high risk of serotonin syndrome: Hydroxocobalamin IV 5–10 g If low risk of serotonin syndrome: Angiotensin II 20 ng/kg/min, up to 80 ng/kg/min (maximum dose) Bolus of Methylene Blue 1–2 mg/kg followed by a continuous infusion of 0.25 mg/kg/h for 6 hours
Rescue	Vitamin C (1.5 g every 6 hours) Consider IV Thiamine

Hb: hemoglobin; IV: intravenous

Chest Closure and Transport to Intensive Care Unit (ICU)

During chest closure, hemodynamic deterioration may ensue. Some patients with inadequate intravascular volume can experience mild hypotension, managed with fluids administration. In individuals with poor ventricular function or patients currently receiving inotropic agents, additional volume or inotropic support may be required.

After the chest is closed, the patient can be moved to ICU. Disconnect monitoring sequentially is a good way to avoid a blind period in which the patient has no vital parameter actively monitored.

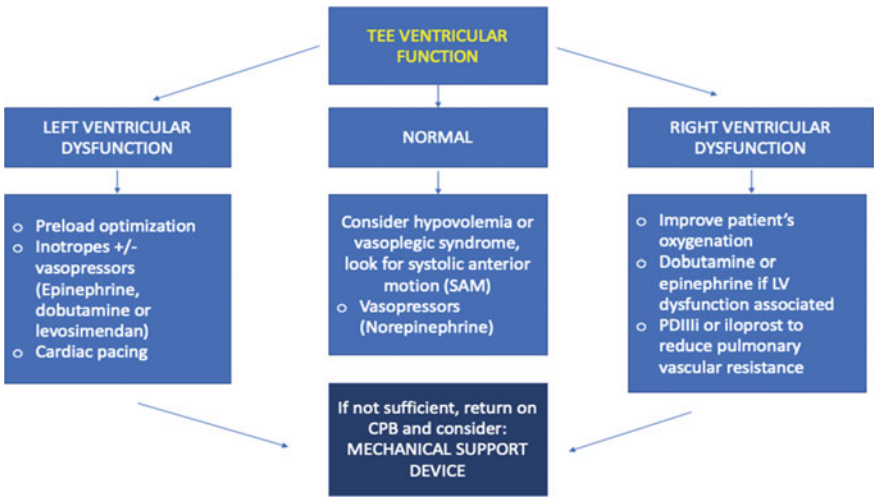

Fig. 3 TEE-guided therapeutic approach for difficult weaning. TEE transesophageal echocardiography, SAM systolic anterior motion, CPB cardiopulmonary bypass, LV left ventricle

Recommended Reading

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