CHEST Postgraduate Education Corner
CONTEMPORARY REVIEWS IN CRITICAL CARE MEDICINE

Perioperative Risk and Management in Patients With Pulmonary Hypertension

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Pulmonary hypertension (PH) is a known risk factor for perioperative complications. Unlike in the case of cardiac surgery, PH is currently not listed as an independent risk factor for postoperative complications in guidelines for the management of noncardiac surgery. Despite the paucity of data, though, patients with PH are often counseled against having elective procedures because early and sudden postoperative deaths have been reported. Patients with PH are unable to accommodate alterations in right ventricular (RV) preload or afterload induced by fluid shifts, medications, or changes in the autonomic nervous system precipitated by hypoxia or hypercapnia. These factors become magnified in situations of added stress such as surgical intervention. Systemic hypotension and arrhythmias may precipitate RV ischemia, further worsening RV function. Patient and surgical characteristics and choice of anesthetic technique are crucial factors in perioperative management. The two main principles of perioperative management are the prevention of systemic hypotension (risk of RV ischemia) and the prevention of acute elevations in pulmonary arterial pressure (risk of RV failure). Close monitoring, optimization of systemic BP, pain control, oxygenation and ventilation, avoidance of exacerbating factors, and use of vasopressors and pulmonary vasodilators as necessary are essential elements of management. Understanding the pathophysiology, cause, and severity of PH in the individual perioperative patient allows accurate risk assessment, optimization of PH and RV function prior to surgery, and appropriate intraoperative and postoperative management. ***CHEST 2013; 144(1):329–340***

Abbreviations: CO = cardiac output; LV = left ventricular; PAH = pulmonary arterial hypertension; PAP = pulmonary arterial pressure; PH = pulmonary hypertension; PVR = pulmonary vascular resistance; RV = right ventricular; SVR = systemic vascular resistance; TEE = transesophageal echocardiography

Pulmonary hypertension (PH)[1] is a known risk factor for perioperative complications. Patients with PH are unable to accommodate alterations in preload or afterload induced by fluid shifts, medications, or changes in the autonomic nervous system. These factors become magnified in situations of added stress, such as surgical intervention.[2-9] Understanding the pathophysiology, cause, and severity of PH in the individual perioperative patient allows accurate risk assessment, optimization of PH and right ventricular (RV) function prior to surgery, and appropriate intraoperative and postoperative management.

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Mechanisms Responsible for Perioperative Complications in Patients With PH

Pulmonary arterial pressure (PAP) is a function of left atrial pressure, cardiac output (CO), and pulmonary vascular resistance (PVR) (Fig 1). Several situations that may occur during the perioperative period can precipitate worsening PH, RV ischemia, or RV dysfunction (Table 1). Positive pressure ventilation may compromise venous return, thus reducing RV

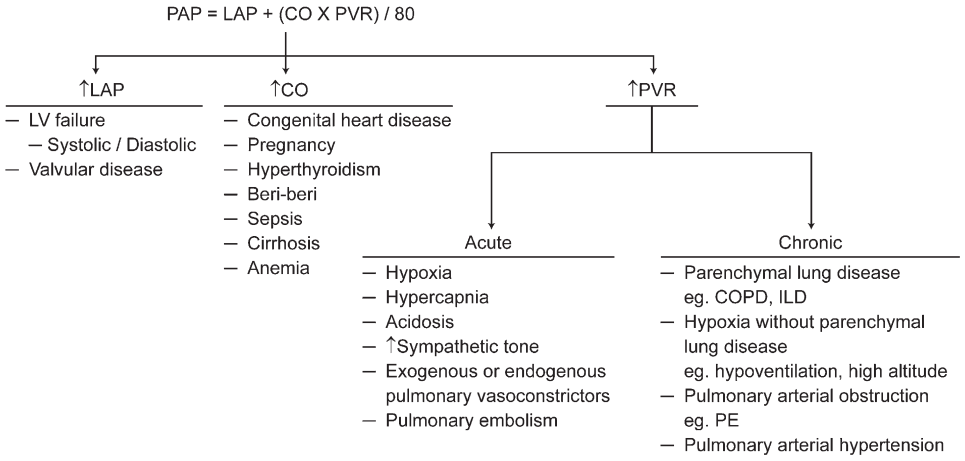

FIGURE 1. Schema showing physiologic determinants of PAP and pathologic conditions contributing to each determinant. CO = cardiac output; ILD = interstitial lung disease; LAP = left atrial pressure; LV = left ventricular; PAP = pulmonary arterial pressure; PE = pulmonary embolism; PVR = pulmonary vascular resistance.

preload and limiting CO. Positive pressure ventilation may also overdistend alveoli, increasing PVR[10] and reducing left ventricular (LV) preload. RV volume overload associated with fluid shifts during surgery may reduce LV cavity size and compromise LV filling because of ventricular interdependence, leading to decreased CO and hypotension. In normal individuals, RV perfusion occurs during both systole and diastole because of the favorable gradient between systolic and diastolic aortic pressures and the corresponding RV intramyocardial pressures. In patients with PH, as RV systolic pressure approaches aortic systolic pressure, systolic coronary blood flow to the right ventricle is compromised. As the right ventricle fails and RV end-diastolic pressure rises, diastolic perfusion becomes limited,[11] contributing to RV ischemia and worsening RV function, leading to further reductions in CO and systemic BP[12] and, eventually, death.[13]

Table 1—*Factors Contributing to Pulmonary Hypertension in the Perioperative Period*

Factors
Preoperative pulmonary hypertension
Increased sympathetic tone (eg, pain, airway instrumentation, surgical manipulation)
Hypoxia
Ischemia-reperfusion injury
Fluid overload
Positive pressure ventilation
Left ventricular systolic or diastolic failure
Embolism: thromboembolism, CO_2 embolism, air embolism, amniotic fluid embolism
Acidosis
Acute lung injury/ARDS
Loss of vasculature (eg, pneumonectomy)
Pharmacologic agents: protamine

Gradual increases in RV afterload are better tolerated than acute elevations.[14] If severe and rapid enough, sudden increases in RV afterload due to an acute increase in PAP may precipitate RV failure and lower RV stroke volume.[14,15] These increases can be related to hypercarbia, hypoxia, acidosis, and noxious stimuli such as pain and airway instrumentation. Abrupt increases in mean PAP above 40 mm Hg in previously normal individuals precipitate decreases in RV stroke volume.[11] Efforts at volume loading may be ineffective or even deleterious because volume loading may actually worsen RV failure and further diminish LV filling.

Other factors, including arrhythmias, decreases in CO from arrhythmias, or ischemia resulting in hypotension, and the side effects of anesthetic agents may also play a role. Some surgical procedures may pose a special risk for the patient with PH, such as hip replacement, which may involve pulmonary embolization of cement, air, and bone marrow during placement of the femoral component, and liver transplant, which may produce microembolization as well as the need for rapid and large amounts of volume infusion that the compromised pulmonary circulation may be unable to handle.[16]

PH and Surgical Risk

Cardiac Surgery

The negative impact of PH on cardiac surgical outcomes is well known from studies[7,8,17,18] showing mortality rates of up to 25%. Although multiple factors may be responsible (Table 2), the risk of RV dysfunction and ischemia is significant particularly after extracorporeal circulation is stopped. In a retrospective study of 2,066 patients undergoing cardiopulmonary bypass, PH was the only baseline variable

Table 2—*Identified Risk Factors for Perioperative Complications in Patients With Preoperative PH Undergoing Cardiac Surgery*

Risk Factors
Increased risk
Presence of preoperative PH
mSBP/mPAP < 4 after anesthesia induction[19]
mPAP > 50 mm Hg and PVR = 8.6 WU[20]
Cardiac transplant
PVR > 4 WU[21,22]
PVR ≥ 5 WU despite acute vasodilator testing[23]
PAP systolic > 60 mm Hg, PVR > 6 WU, mean TPG > 15 mm Hg despite maximal vasodilator therapy[24]
Decreased risk
PVR/SVR < 0.33 on 100% oxygen and inhaled NO[25]
A decrease of PVR/SVR ≥ 20% compared with baseline in response to 100% oxygen and inhaled NO[25]
Cardiac transplant: TPG < 12 mm Hg or PVR < 3 WU

The majority of patients in Balzer et al[25] had congenital heart defects. mPAP = mean pulmonary artery pressure; mSBP = mean systemic BP; NO = nitric oxide; PAP = pulmonary arterial pressure; PH = pulmonary hypertension; PVR = pulmonary vascular resistance; SVR = systemic vascular resistance; TPG = transpulmonary gradient; WU = Wood units.

independently predictive of perioperative mortality (OR, 2.1).[8] In patients undergoing elective mitral valve replacement, those with severe PH had a higher mortality (10.5%) than those without PH (3.6%).[20]

One of the most important components in the evaluation of candidacy for cardiac transplantation is the assessment of the pulmonary circulation and the RV function.[23] Studies suggest that PH and acute RV failure can account for 19% of mortality and 50% of complications after cardiac transplant,[26] and that "fixed" PH is associated with an increased 30-day mortality rate.[25] Although no clear cutoff value has been identified, it is evident that the risk posed by PH in the patient being evaluated for cardiac transplant is linear and is directly proportional to the transpulmonary gradient and the PVR.[21-26] Once PH is diagnosed, most cardiac transplant programs assess reversibility with the use of pharmacologic agents (Table 2). There is no consensus definition for significant vasoreactivity, and different institutions use different criteria.

Evidence suggests that in patients undergoing cardiac surgery, the extent of pulmonary vasoconstriction correlates with the induced endothelial injury[27] reflected in increased levels of thromboxane A2[28] and endothelin[29] and decreased levels of nitric oxide and prostacyclin.[30] These may depend on the preoperative status of the pulmonary vascular bed, intraoperative vasospastic stimuli, the impact of surgical correction on the cause of PH, and postoperative factors such as hypoxia and adrenergic tone. In view of this, patients undergoing cardiac surgery are evaluated for the cause and severity of the PH.

Noncardiac Surgery

Most of the literature regarding the role of PH in perioperative morbidity and mortality in patients undergoing noncardiac surgery is based on small series and remains poorly defined (Table 3).[2,4,5,31,32] PH is currently not listed in the American Heart

Table 3—*Summary of Case Series in Patients With PH Undergoing Nonccardiac Surgery*

Study/Year	No.	Cause of PH[a]	Method of Diagnosis	NYHA, %	PH-Specific Therapy, %	Major Surgery, %	General Anesthesia, %	Morbidity,[b] %	Mortality, %
Ramakrishna et al[5]/2005	145	PAH	RHC and DE	I/II, 73 III/IV, 27	14	79	100	42	7
Minai et al[2]/2006	28[c]	PAH	RHC	I/II, 38 III/IV, 62	76	86	79	19	18
Lai et al[31]/2007	62	PVH	DE	NA	0	65	58	24.2	9.7
Price et al[32]/2010	28	PAH	RHC	NA	NA	75	50	2[d]	7
Kaw et al[4]/2011	173	PAH and PVH	RHC	NA	NA	100	100	26	1

DE = Doppler echocardiography; NA = not available; NYHA = New York Heart Association; PAH = pulmonary arterial hypertension; PVH = pulmonary venous hypertension; RHC = right-sided heart catheterization. See Table 2 legend for expansion of other abbreviation.

[a] In many of these studies, patients were classified based on pulmonary hemodynamics, and not all patients underwent necessary testing to be identified as clearly having PAH vs PVH. Therefore, the terms PAH and PVH actually refer to precapillary PH and postcapillary PH and not necessarily World Health Organization groups I and II, respectively.

[b] Perioperative morbidity was defined differently depending on the study (see text).

[c] Procedures (n = 21 patients underwent 28 procedures).

[d] Most occurred in the first 48 h after the procedure.

Association/American College of Cardiology Foundation Practice Guideline for noncardiac surgery as an independent risk factor for postoperative complications.[33] Despite the paucity of data, patients with PH are often counseled against having elective procedures because early and sudden postoperative deaths have been reported.[34-37]

Potential complications, including hypotension, respiratory compromise, or RV failure, may occur intraoperatively or in the postoperative period.[2-5,12] Despite the limited literature, several factors have been identified as potential predictors of increased risk of perioperative complications in patients with PH undergoing noncardiac surgery (Fig 2).

In a series of 21 patients with pulmonary arterial hypertension (PAH) undergoing 28 noncardiac surgery procedures, Minai et al[2] found no need for prolonged mechanical ventilation postoperatively and that most patients requiring general anesthesia (12 of 22 [55%]) were extubated successfully in the operating room (Table 3). However, patients with moderate-to-severe PAH had an 18% per procedure mortality.

In a retrospective study of 145 patients with PH (diagnosed by right-sided heart catheterization or Doppler echocardiography) undergoing noncardiac surgery, Ramakrishna et al[5] reported 7% early mortality (≤30 days postoperative) and found that respiratory failure (60%) and RV failure (50%) were the most frequent contributing factors. Sixty patients (42%) had one or more short-term morbid events, including respiratory failure (28%), cardiac dysrhythmias (12%), and congestive heart failure (11%).

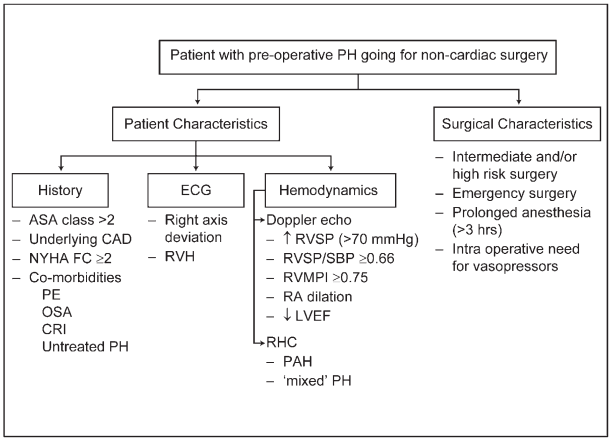

FIGURE 2. Identified risk factors for perioperative complications in patients with preoperative PH undergoing noncardiac surgery. ASA = American Society of Anesthesiologists; CAD = coronary artery disease; CRI = chronic renal insufficiency; LVEF = left ventricular ejection fraction; NYHA FC = New York Heart Association functional class; OSA = obstructive sleep apnea; PAH = pulmonary arterial hypertension; PH = pulmonary hypertension; RA = right atrial; RHC = right-sided heart catheterization; RVH = right ventricular hypertrophy; RVMPI = right ventricular myocardial performance index; RVSP = right ventricular systolic pressure; SBP = systolic BP. See Figure 1 legend for expansion of other abbreviations. (Based on risk factors identified in Minai et al,[2] Kaw et al,[3] Kaw et al,[4] Ramakrishna et al,[5] Lai et al,[31] and Price et al.[32])

Lai et al[31] found a postoperative morbidity and mortality of 24% and 9.7%, respectively, in 62 patients with severe PH (diagnosed by Doppler echocardiography). Major causes of morbidity included delayed extubation (21%), heart failure (9.7%), and major arrhythmias (3.2%), but the overall frequency of adverse outcomes was similar for patients with and without PH. These results may reflect, in part, the lack of accurate hemodynamic characterization in these patients. Price et al[32] retrospectively reviewed complications in 28 patients with PH (mostly PAH) who underwent noncardiothoracic, nonobstetric surgery. Most of the complications occurred within 48 h of surgery. Emergency and major procedures had higher complication rates than nonemergency and minor surgeries. Overall, perioperative morbidity and mortality were 29% and 7%, respectively.

In the first case-control study in patients with PH undergoing noncardiac surgery, Kaw et al[4] found that patients with preoperative PH had a higher risk of overall morbidity and mortality (26% vs 2.6%; $P < .0001$; OR, 13), postoperative heart failure (13.5% vs 1.3%; $P = .001$; OR, 11.9), hemodynamic instability ($P = .002$), respiratory failure ($P = .004$), prolonged intubation ($P = .002$), and increased ICU and hospital length of stay ($P = .0008$) than did those without PH. Risk of perioperative complications was highest in patients with PAH or mixed PH (those with pulmonary capillary wedge pressure > 15 mm Hg and PVR > 3 Wood units). By multivariate logistic regression analysis, the presence of PH was an independent predictor of increased risk of perioperative morbidity and mortality (OR, 15.3; $P = .001$). Although most of the these studies are limited by small numbers and lack of comparators, the findings strongly suggest that the presence of PH is a risk factor for perioperative morbidity and mortality in patients undergoing noncardiac surgery.

Perioperative Evaluation and Management

Proper evaluation and medical optimization in the preoperative period (Table 4) and close monitoring with avoidance of noxious stimuli in the perioperative period are critical to a successful outcome. Perioperative medical management of these complex patients often requires a multidisciplinary approach with input from anesthesiologists, PH experts, pharmacists, and surgeons. Management recommendations in this review are based on the literature and the expertise of the authors in managing these patients because evidence-based guidelines are not available.

Table 4—*Preoperative Evaluation and Management in Patients With Preexisting PH*

Evaluation and Management
1. Multidisciplinary team approach
Anesthesiologist, PH physician, surgeon
2. Careful evaluation of need for surgery
Avoidance of emergent surgery if possible
Assessment of risk-benefit of intervention
3. Assessment of cause and severity of PH
History and clinical examination
ECG
Chest radiography
Pulmonary function testing
B-type natriuretic peptide
6-min walk test
Doppler echocardiography
Right-sided heart catheterization (in patients with evidence of RVF)
4. Evaluation of comorbidities
5. Optimization of PH therapy and RV function prior to surgical intervention if possible
Use of PH-specific therapies and diuretics
6. Anticoagulation
Patients on anticoagulation for PAH can be taken off anticoagulation safely in preparation for surgery
Patients on anticoagulation for other reasons (eg, DVT, AF, artificial valves, and so forth) should be bridged with anticoagulants depending on the risk of discontinuation and the surgical risk of bleeding

AF = atrial fibrillation; RV = right ventricular; RVF = right ventricular failure. See Table 2 and 3 legends for expansion of other abbreviations.

Preoperative Evaluation

A preoperative evaluation for PH should be performed routinely in patients undergoing cardiac surgery in view of their increased risk. Based on the evidence summarized previously, we now know that patients with PH undergoing noncardiac surgery are also at increased risk and recommend that patients be evaluated for the cause and severity of the PH prior to surgery (Table 4).

A thorough history and physical examination, ECG, chest radiograph, and Doppler echocardiogram should be performed to assess RV and LV and valvular structure and function. Right-sided heart catheterization should be performed in patients with suspected PH for accurate characterization of pulmonary hemodynamics. Concomitant left-sided heart catheterization is indicated if coronary artery disease or left-sided valvular disease is suspected or if there are doubts about the accuracy of the pulmonary artery wedge pressure measurement. Elevations in right atrial pressure and reductions in CO are of much greater concern than the severity of PA pressure elevation because they indicate RV failure. For patients with RV failure, any surgeries beyond minor should be avoided.

The anesthesiologist should consider several key issues prior to anesthesia, including the risk-benefit ratio of the surgery, the anesthetic technique to be used, the potential for the surgery to undermine fluid balance or increase PVR, and the availability of tools necessary to prevent and treat PH and acute RV failure should it occur. The presence of significant RV dysfunction should prompt reevaluation of the need for surgery. The principles of management include the avoidance of systemic hypotension (risk of RV ischemia), myocardial depression (risk of RV failure due to diminished contractility), acute elevations in PAP (risk of RV failure due to increased impedance), inadequate pain control (risk of increased sympathetic tone and PVR), and respiratory depression. In patients discovered to have PH unexpectedly prior to emergent or urgent surgery, the use of phosphodiesterase-5 inhibitors (such as sildenafil) or inhaled nitric oxide administered prophylactically has been described.[38,39]

Intraoperative and Postoperative Management

A guide to the intraoperative and postoperative management of patients with preexisting PH is shown in Figure 3.

General Considerations: Small doses of benzodiazepines may be given in extremely anxious patients; however, heavy doses of narcotics and sedatives and their combinations should be avoided because they may cause respiratory depression, hypercarbia, and increased PVR. Specific pharmacotherapies being used to treat PH must be continued because withdrawal can precipitate a PH crisis. Even though some of these medications can inhibit platelet aggregation, this is usually a minor effect and excessive surgical bleeding has not been reported. Oxygenation should be well maintained during transport and throughout the procedure.

Avoidance of systemic hypotension, which could precipitate RV ischemia, is a key element in managing these patients. Systemic pressure in patients with PH is determined by a complex interaction between RV and LV filling pressures, PVR and systemic vascular resistance (SVR), and the respective ventricular outputs. In patients with significant PH (in the absence of left-sided cardiac limitation), CO is largely determined by the interaction among RV preload, contractility, and afterload, and the relevant indicators of RV filling are the central venous or right atrial pressures. Conversely, it is important to remember that central venous pressure is not an accurate indicator of LV preload in patients with PH. This complex balancing act requires assessment of acid base status and oxygenation, attention to details such as pain relief and ventilator management strategies, and often, invasive hemodynamic monitoring.

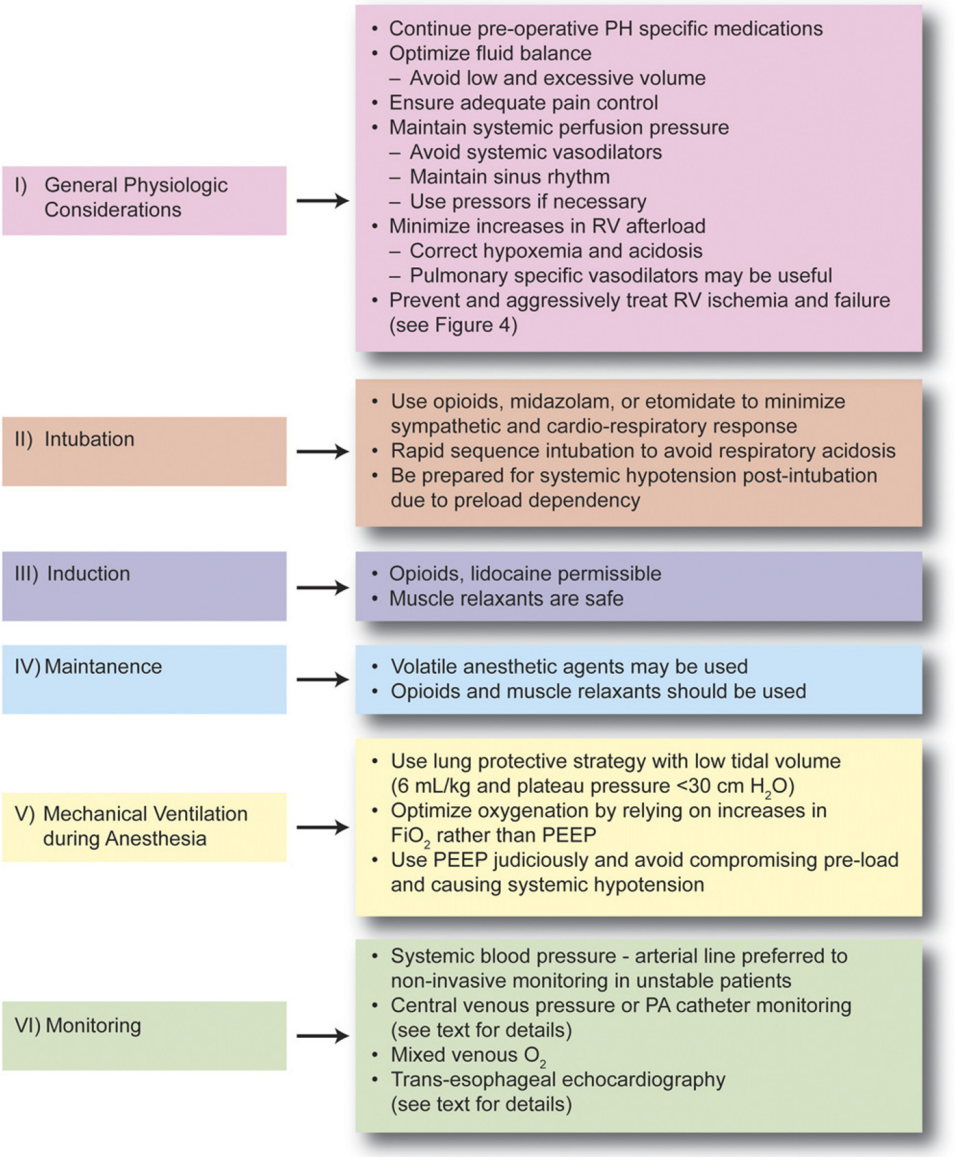

FIGURE 3. Intraoperative and postoperative management in patients with preexisting PH. PA = pulmonary artery; PEEP = positive end-expiratory pressure; RV = right ventricular. See Figure 2 legend for expansion of other abbreviations.

Monitoring: Standard American Society of Anesthesiologists monitors (electrocardiography, pulse oximetry, temperature) should be applied. An indwelling arterial catheter may be helpful to monitor the systemic BP in response to induction of general anesthesia or regional block. Central venous pressure monitoring is also very useful for the assessment of changes in RV filling pressure and the detection of new onset or worsening of tricuspid insufficiency. In the intraoperative and postoperative settings, PA catheter monitoring has several advantages over noninvasive monitoring, including accurate assessment of PAP for proper use of pulmonary vasodilator therapy, measurement of CO, mixed venous oxygen saturation, calculation of PVR, and accurate measurement of both central venous pressure and pulmonary capillary wedge pressure to determine the need for vasopressors and/or fluids. Thermodilution CO must be interpreted with caution in patients with anatomic shunting or significant tricuspid regurgitation.

Anesthesia: After induction and intubation, a transesophageal echocardiography (TEE) probe can be inserted to evaluate the PAP and RV size and function. Acute dilatation or reduced contraction of the right ventricle can help direct fluid or inotrope administration. There are no established specific indications for TEE monitoring, but it may be useful in patients with PH undergoing major or prolonged surgery that may be associated with significant blood loss or impaired

tissue perfusion with metabolic acidemia. Insertion of a TEE probe can have hemodynamic effects similar to those of endotracheal intubation. Thus, the risks and benefits of TEE insertion must be weighed carefully and insertion carried out with caution if it is deemed necessary.

The choice of anesthetic technique and anesthetic management are crucial factors in the maintenance of cardiovascular stability in patients with PH. Anesthetic agents may depress myocardial contractility, decrease SVR and venous return, increase PVR, or exacerbate hypoxia or hypercapnia. Irrespective of the anesthetic technique, however, an adequate level of anesthesia should be maintained to produce effective pain control.

General anesthesia is the most commonly used technique. Preoxygenation with 100% oxygen to achieve end-tidal oxygen concentrations above 90% mitigates the increased risk of hypoxemia due to a reduction in functional residual capacity that frequently occurs after induction. Effective mask ventilation to avoid increases in arterial CO_2 and achieve adequate oxygenation should precede intubation.

Etomidate has minimal impact on myocardial contractility and SVR and, combined with an opiate, is often the preferred induction agent.[40,41] Thiopental, nitrous oxide, etomidate, propofol, fentanyl, and sufentanyl have minor or variable effects on PVR. Propofol and sodium pentothal should be avoided because they decrease the systemic BP cardiac contractility. Ketamine decreases PVR and increases SVR and may be the drug of choice in some children with congenital heart defects.[42] Intubation should be performed by experienced hands in a rapid and smooth manner. IV or nebulized milrinone or epoprostenol, IV nitroglycerin, inhaled nitric oxide, or nebulized epoprostenol or iloprost are all used before induction for the prevention of pulmonary hypertensive responses, although their efficacy has not been studied adequately and selection depends largely on physician experience and preference.

In general, single-lung ventilation should be avoided because it decreases blood flow to the nonventilated (collapsed) lung, resulting in acute exacerbation of PH and potential RV failure. Single-lung ventilation may be necessary for procedures such as lung transplant. Severe PH following transient occlusion of one of the pulmonary arteries by balloon inflation indicates that a patient is unlikely to tolerate one lung ventilation or pneumonectomy[43] and may require cardiopulmonary bypass for procedures such as lung transplant.

Several techniques using regional anesthesia have been used successfully in patients with PH[10,12,44] and none has been proven to be superior to another as long as the agents are titrated to hemodynamics. When appropriate for the planned surgery, a peripheral nerve block or local anesthesia is preferred. No studies have compared general and regional anesthesia in patients with PH. If the surgical procedure can be performed with either regional or general anesthesia, the choice depends on the severity of the PH and the invasiveness of the surgical procedure. Regional anesthesia has been used safely for cesarean section and for procedures that do not require a high neuraxial block. Epidural anesthesia is usually preferred to spinal anesthesia because of its more gradual and, therefore, controllable onset. Even if regional anesthesia is selected, central hemodynamic monitoring is often indicated because of the potential deleterious effects on venous return and the adequacy of RV performance. For the management of patients with severe PH undergoing procedures involving major blood loss or prolonged surgery time, general anesthesia with invasive monitoring is considered preferable to regional.

Pain control is very important in patients with PH to mitigate adverse autonomic reflexes, and nerve or neuraxial blocks are beneficial for perioperative analgesia. Epidural anesthesia has been used successfully in patients with PH undergoing childbirth to limit the magnitude (and therefore the potential sympatholytic effects) of the block.[45] It is preferable to avoid spinal anesthesia in most surgeries involving patients with PH because of profound sympatholytic effects and rapid onset. Cautious administration of parenteral narcotics may prevent or reverse sympathetically mediated increases in PVR such as would result from surgical stimulation.

For the maintenance of general anesthesia, patients with PH typically receive inhalational volatile anesthetics or IV anesthetics with opiates. These must be titrated carefully to BP, PAP, and ventricular function because most general anesthetic agents and sedatives decrease SVR and may cause hypotension in patients with fixed CO. Inhaled anesthetics can also depress myocardial function in a dose-related fashion. Although studies have not shown superiority of any particular anesthetic agent over others in terms of their effects on the pulmonary vasculature,[46,47] most anesthesiologists avoid nitrous oxide because it may increase PVR and contribute to right-sided heart ischemia.[48,49] In titrating anesthetic agents, one should remember that patients with chronic severe PH may have altered metabolism of drugs because of chronic venous congestion and end-organ dysfunction. Additional details about anesthetic management in patients with PH have been reviewed elsewhere.[10,12,50]

During maintenance, the anesthesiologist must avoid exacerbating risk factors for RV compromise such as hypothermia, hypoxia, hypercarbia, acidosis, and hyper- or hypovolemia (Fig 3). Monitoring blood

gases, temperature, and ventilation, and maintaining an adequate anesthetic depth are required to achieve these goals. Lung-protective ventilator strategies using low tidal volumes may be helpful to avoid hyperinflation of the lungs and to minimize PVR by keeping lung volume near functional residual capacity. Lung hyperinflation may also result in unwanted increase in end-expiratory pressure, which may adversely affect venous return and RV preload.

Specific surgeries carry greater risks to patients with PH because of duration, magnitude of volume shifts and blood loss, and effects on cardiovascular or pulmonary function. As discussed earlier, lobectomy, and especially pneumonectomy, may transiently or permanently increase PVR. Such procedures are contraindicated when baseline PVR is more than mildly elevated. Laparoscopic procedures may increase intraabdominal pressure sufficiently to impair lung compliance or decrease venous return. Moreover, CO_2 insufflation usually leads to respiratory acidosis, which must be corrected by an appropriate increase in minute ventilation. If acute acidemia cannot be compensated for by an increase in minute ventilation, then an alkalinizing agent such as sodium bicarbonate should be considered.

Postoperatively, patients are at risk of developing worsening PH and RV ischemia as the effects of regional and inhalational anesthetics and opioids, used during surgery, wear off. Pain increases the PVR, but systemic opiates may have the same effect via their tendency to cause respiratory acidosis. Neuraxial or regional blocks may be beneficial in this context because they relieve pain without depressing respiratory drive. Adjunctive treatment with nonsteroidal antiinflammatory agents may also improve pain control. Life-threatening rebound PH may occur in patients being weaned from pulmonary vasodilators (especially inhaled nitric oxide) or mechanical ventilation. The possibility of rebound PH should be anticipated and treated with management of potential precipitating factors and gradual weaning of pulmonary vasodilators.[38,51,52] Sildenafil may be helpful to minimize the rebound PH occurring during removal of inhaled nitric oxide.[51]

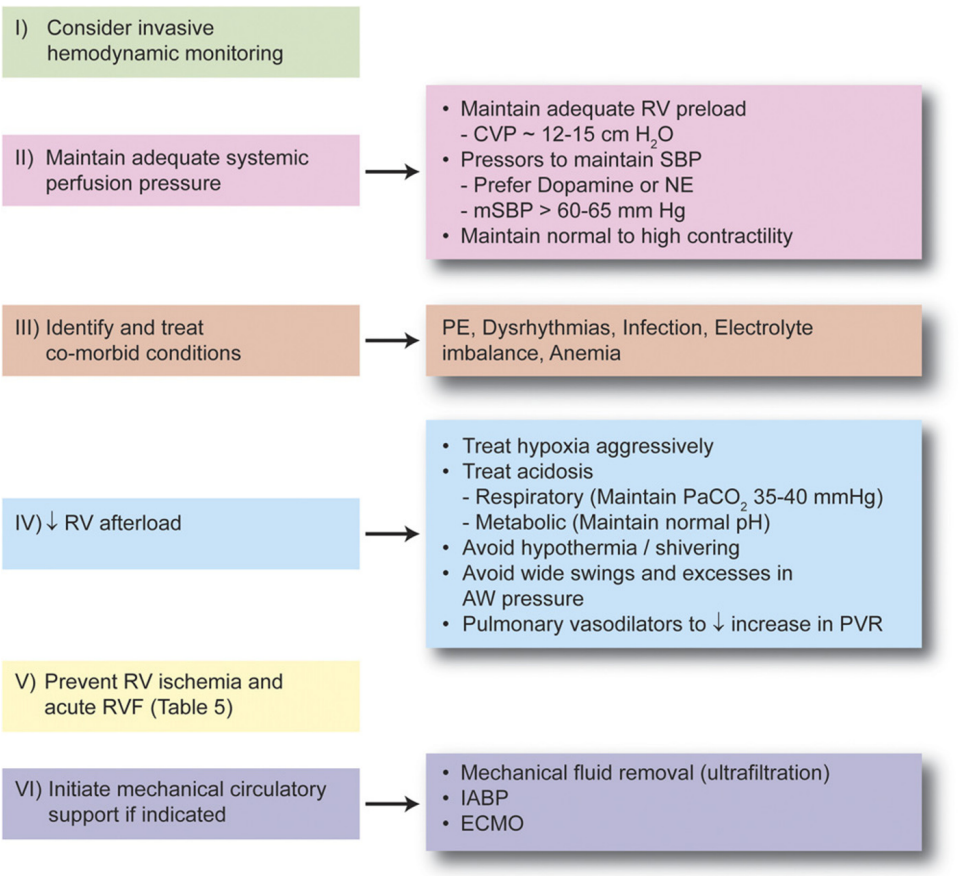

FIGURE 4. Principles of management of RV ischemia and acute RV failure. CVP = central venous pressure; ECMO = extracorpeoreal membrane oxygenation; IABP = intraaortic balloon pump; mSBP = mean systemic BP; NE = norepinephrine; RVF = right ventricular failure. See Figure 1, 2, and 3 legends for expansions of other abbreviations.

Management of Perioperative PH Crisis

Various stressors may precipitate RV failure and cardiovascular collapse in perioperative patients with PH. When preventive measures fail, prompt restoration of adequate systemic perfusion pressure and reduction of PVR (if possible) are essential[10,12,50] (Fig 4). In the setting of hypotension, PA catheter monitoring may allow a more rational approach (Fig 5). Hypotension with a stable CO indicates that reduced SVR is the causative factor, and the usual recommendation is to use a combined inotropic-vasopressor agent such as norepinephrine (which can lower the ratio of PAP to systemic BP without a change in CO) or a systemic vasoconstrictor such as vasopressin.[53] Dopamine and epinephrine may be less desirable because they tend to increase heart rate and myocardial oxygen consumption more than norepinephrine.[9]

Systemic hypotension with an increased right atrial pressure and PVR suggests that increased RV afterload is the causative problem, and once systemic BP is stabilized using pressors, pulmonary vasodilator therapy is indicated to reduce PVR and the PVR to SVR ratio and (ideally) increase CO. Short-acting, pulmonary-specific vasodilators that can be titrated rapidly such as inhaled NO,[54-57] inhaled prostacyclin analogs,[58-63] or oral or parenteral sildenafil,[9,64,65] are recommended in these patients. Promising therapies that require further study include parenteral levosimendan[66,67] and inhaled[68] or IV use of sildenafil and IV milrinone[69-71] and nitrogylcerin.[72]

If these interventions fail, systemic BP may be improved by intraaortic balloon counterpulsation.

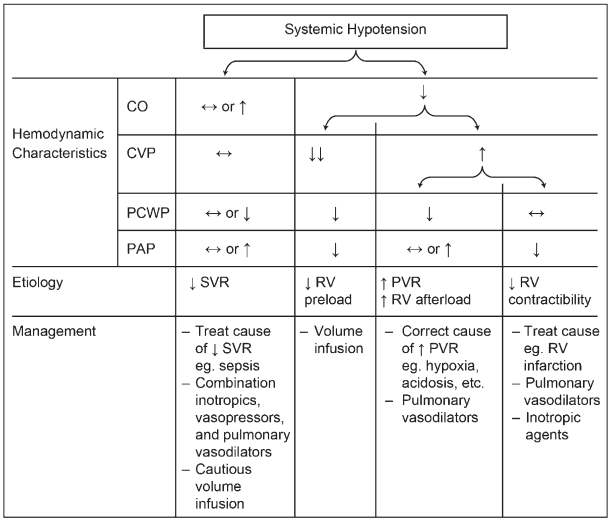

Figure 5. Depiction of various hemodynamic subsets contributing to systemic hypotension as determined by pulmonary artery catheter illustrating different therapeutic approaches for each subset. PCWP = pulmonary capillary wedge pressure; SVR = systemic vascular resistance. See Figure 1, 3, and 4 legends for expansion of other abbreviations.

Mechanical assistance with an LV assist device can also help LV recovery because hypotension may also induce LV ischemia. If these techniques fail, extreme measures such as extracorporeal membrane oxygenation[73] may be life saving. Mechanical RV assist devices may potentially damage the pulmonary microcirculation and are currently not recommended. Atrial septostomy may be considered as a palliative measure or a bridge to lung transplant but the mortality is very high in emergency situations.[73] All of these interventions must be implemented emergently before irreversible myocardial or end-organ damage occurs.

Our recommendations are tempered by the lack of appropriately controlled studies dealing with many facets of the evaluation and management of PH in the perioperative period. Much of the medical literature consists of case reports or case series. In addition, definitions and characterization of PH are inconsistent among studies, with some relying on Doppler echocardiogram and others on right-sided heart catheterization. Many reports include heterogeneous patient populations, including patients from a number of different World Health Organization groups. These limitations severely impair our ability to draw firm conclusions.

Summary

PH is a risk factor for both cardiac and noncardiac surgeries. A careful preoperative evaluation should be performed in all patients with PH, and those deemed at higher risk by virtue of significant reductions in functional capacity or abnormalities on echocardiogram should undergo a preoperative right-sided heart catheterization to better characterize severity. Careful planning among PH specialists, anesthesiologists, and surgeons can help avoid unnecessary complications. Multiple pharmacotherapies, including specific PAH drugs, vasopressors, and positive inotropes, have been used to treat patients with PH perioperatively but have not been studied systematically, so firm specific recommendations cannot be made. On the other hand, observation of fundamental management principles such as optimization of fluid volume, systemic BP, and acid base balance; avoidance of hypoxemia and hypercapnia; and good pain control clearly are important to achieve desirable surgical outcomes.

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