Preoperative Risk Assessment of Pulmonary Arterial Hypertension Patients Undergoing General Surgery

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Pulmonary arterial hypertension (PAH) is a disease of the pulmonary vasculature that is characterized by a progressive increase in pulmonary vascular resistance (PVR) and pulmonary artery pressure (PAP) resulting in the development of right ventricular (RV) failure, inadequate oxygenation, and ultimately death. Anesthesia and surgery, both cardiac and noncardiac, are associated with significantly increased morbidity and mortality in patients with PAH due mainly to RV failure, arrhythmias, postoperative hypoxemia, and myocardial ischemia. Preoperative risk assessment and successful management of patients with PAH undergoing general surgery involves an understanding of the pathophysiology of the disease, analysis of preoperative and operative risk factors, intraoperative management, and early recognition and treatment of postoperative complications.

Classification

For the physician who is treating a perioperative patient with pulmonary hypertension, it is important to know the underlying etiology of the pulmonary hypertension. Five major categories of pulmonary hypertension are currently classified by the World Health Organization (Group 1: PAH; Group 2: pulmonary venous hypertension related to left heart disease; Group 3: pulmonary hypertension associated with hypoxic respiratory disorders; Group 4: pulmonary hypertension due to chronic thromboembolic disease; and Group 5: miscellaneous causes). PAH is diagnosed hemodynamically as a mean PAP (mPAP) greater than 25 mmHg at rest or greater than 30 mmHg with exercise, PVR greater than 3 Wood units, and pulmonary artery occlusive pressure (PAOP) of 15 mmHg or less (ie, evidence of "precapillary" pulmonary hypertension in patients who fit WHO Group I clinical characteristics).

Pulmonary hypertension regardless of etiology is associated with increased surgical risk compared to patients without pulmonary hypertension. However, the perioperative risk and management among these patients may differ, particularly for patients with pulmonary venous hypertension (ie, "postcapillary" pulmonary hypertension; mPAP greater than 25 mmHg, PVR less than 3 Wood units, PAOP greater than 15 mmHg) or "mixed" pulmonary hypertension (mPAP greater than 25 mmHg, PVR greater than 3 Wood units, PAOP greater than 15 mmHg). This document will address patients with PAH, though most of the principles discussed may apply to patients with other categories of pulmonary hypertension regardless of etiology.

Pathophysiology

The pulmonary vasculature is normally a low resistance, high capacitance circuit compared to the systemic circulation, which is a high resistance circulation. The precapillary pulmonary arterioles have thinner media and fewer smooth muscle cells, resulting in greater compliance. In addition, the cross-sectional area of the pulmonary vascular bed is large, with a great capacity for the recruitment of vessels to accommodate increases in flow (cardiac output) up to three- or fourfold without an increase in PAP. PAH is associated with a combination of pulmonary arteriolar vasoconstriction from vascular smooth muscle cell contraction, vascular remodeling, and in-situ thrombosis. Increases in PVR and PAP increase RV afterload, leading progressively to hypertrophy, chamber dilation, and systolic dysfunction.

Symptoms of the disease are first noted when the right ventricle is unable to increase contractility sufficiently to augment left ventricular (LV) preload and cardiac output during exercise. As the disease progresses, LV filling and cardiac output may be

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Table 1. Risk Stratification of Noncardiac Surgical Procedures

Low-Risk Operations
Dermatologic surgeries
Endoscopic procedures
Cataract surgery
Breast surgery
Intermediate-Risk Operations
Carotid endarterectomy
Head and neck surgery
Gynecologic surgery
Gastrointestinal/intraabdominal surgery
Orthopedic surgery
Prostate surgery
Thoracic surgery
High-Risk Operations
Emergent major surgery
Aortic or other major vascular surgery
Liver transplantation
Other major operations with anticipated large fluid shifts and/or blood loss

decreased even at rest as a result of reduced RV stroke volume and impaired LV diastolic filling related to the leftward shift of the interventricular septum. Thus, PAH patients presenting for surgery may have varying degrees of RV dysfunction and remodeling.

Potential Adverse Hemodynamic Effects of Anesthesia

Since, for the most part, the pulmonary vasculopathy in patients with PAH is associated with a sustained elevation in PVR and PAP with relatively little vascular reactivity, anesthetic administration for surgery may cause significant systemic hypotension due to greater systemic than pulmonary vasodilation and a limited ability of the right ventricle to compensate with an increase in cardiac output. In addition, the negative inotropic effects of some anesthetic agents may exacerbate hypotension and precipitate RV failure. RV failure may be manifest by an increase in RV diastolic and right atrial pressures, and superimposed myocardial ischemia may occur as a result of reduced coronary perfusion pressure in the setting of systemic hypotension in a ventricle with high myocardial oxygen consumption due to increased wall stress that can be compounded by tachycardia.

In contrast to the systemic arteries, pulmonary vessels constrict with hypoxia and relax in the presence of hyperoxia. Pulmonary vasoconstriction and acute increases in PVR also occur in the presence of hypercarbia, acidosis, hypothermia, increased sympathetic tone (eg, pain or agitation), and increased endogenous or exogenous mediators such as catecholamines. Therefore, anesthesia and surgery can lead to hemodynamic deterioration and collapse as a result of acute increases in PVR and RV workload, systemic hypotension, myocardial ischemia, and progressive RV failure.

Preoperative Risk Assessment: Predictors of Good and Poor Outcome

There is limited evidence-based literature describing the perioperative risk of morbidity and mortality in patients with PAH undergoing noncardiac surgery, with most of the reports being focused on patients with pulmonary hypertension undergoing cardiopulmonary surgeries, usually with cardiopulmonary bypass. Cardiac surgery and cardiopulmonary bypass are associated with an increased risk of morbidity and mortality compared with noncardiac operations, independent of the presence of pulmonary hypertension. However, compared with other "high-risk" patient populations undergoing noncardiac surgery, the perioperative risk in patients with PAH appears to be greater.[1-3] Moreover, the risks associated with PAH seem to be more frequent than with other etiologies of pulmonary hypertension.[4] Perioperative risk assessment in such patients should involve an individualized approach taking into account the type of surgery, the patient's functional capacity, hemodynamic severity of the PAH and RV function, and any comorbid conditions. Patients with low-risk clinical characteristics and/or those who are to undergo low-risk operations will generally have a good outcome, whereas those who have high-risk features and/or those undergoing intermediate- to high-risk surgeries with general anesthesia have much poorer outcomes.

Type of Surgery Predicts Perioperative Risk

The type of noncardiac surgery being performed significantly influences the perioperative risk (**Table 1**). Ramakrishna et al. published the only study to date of perioperative outcomes in patients with pulmonary hypertension undergoing noncardiac surgery. They retrospectively analyzed the outcomes of a heterogeneous group of 145 patients with pulmonary hypertension diagnosed by echocardiography undergoing noncardiac surgery (note that the types of surgeries categorized as low versus intermediate to high risk in this study differ from **Table 1**), and they found that short-term perioperative mortality was 7%. Thoracic followed by orthopedic surgeries were associated with the highest perioperative morbidity.[3,5]

Thoracic surgery may be associated with changes in intrathoracic pressure, lung volumes, and oxygenation that can acutely increase PVR and reduce RV preload and cardiac output with a substantial risk of hemodynamic collapse. Orthopedic surgeries, such as hip or knee replacement, can lead to embolization of air, bone marrow, or cement to the pulmonary circulation that can cause hypoxia, substantial increases in PVR, and acute RV failure. Pneumoperitoneum associated with laparoscopic surgeries may compromise cardiovascular hemodynamic status by reducing ventricular preload and increasing afterload. Procedures that cause rapid blood loss may lead to hypotension and hemodynamic deterioration in the setting of PAH and RV systolic and diastolic dysfunction where RV stroke volume and cardiac output are dependent on adequate preload. Gynecologic surgery in nonpregnant women with PAH may be associated with low to high risk, depending on the clinical setting and surgery type. Cesarean section has been performed successfully in pregnant women with PAH in isolat-

ed small reports. However, it must be emphasized that pregnancy is poorly tolerated in patients with PAH and is contraindicated because of the very high associated maternal and fetal mortality rates. Marked increases in hemodynamic stress and fluid shifts associated with labor and both vaginal and cesarean deliveries are associated with a high puerperal mortality rate, which was 24% in one study of patients with Eisenmenger syndrome.[6] Since most of these deaths occur well after surgery, they are probably not related to anesthesia per se but rather to fluid shifts and neurohormonal changes. Although elective surgery is generally not recommended in patients with PAH because of increased risk, laparoscopic tubal ligation may be performed with relatively low risk in patients with PAH and is a consideration for women of childbearing age who are not candidates for double barrier methods of contraception.[7,8] Alternatively, the Essure micro-insert device is an attractive method of permanent contraception that is implanted noninvasively and appears to be very effective. Other reports of successful outcomes of surgery include patients with PAH undergoing cholecystectomy, hysterectomy, and femoral artery and abdominal aortic aneurysm repairs.[9-11]

Low- Versus High-Risk Clinical Characteristics Predict Surgical Outcome

Ramakrishna et al found that in 145 adult patients with pulmonary hypertension undergoing noncardiac surgery under general anesthesia, New York Heart Association (NYHA) functional class II or higher, right-axis deviation on electrocardiography, RV hypertrophy by 2D-echocardiography, Doppler RV index of myocardial performance 0.75 or higher, RV systolic pressure/systolic blood pressure ratio 0.66 or higher, and a history of pulmonary embolism were associated with increased morbidity and mortality.[3] Pulmonary artery catheterization was not routinely performed in this patient population.

In the absence of more evidence-based literature, other clinical factors that are predictors of perioperative risk are generally felt to be similar to those known to correlate with survival in PAH,[12] and they include patient's functional status and indices of the severity of PAH and RV function, as well as patient comorbidities. Although the PAP itself has not been clearly demonstrated to be an independent predictor of survival in PAH, in children with PAH undergoing noncardiac surgery or catheterization, suprasystemic PAP is a significant risk factor for major perioperative complications, including cardiac arrest and pulmonary hypertensive crisis.[13] In addition, Krowka et al found that the perioperative mortality rate was 100% in patients with portopulmonary hypertension and mPAP of 50 mmHg or greater undergoing liver transplantation, whereas survival was much better in patients with an mPAP under 35 mmHg.[14]

A complete perioperative assessment in patients with PAH should involve transthoracic echocardiography, electrocardiography, assessment of NYHA/WHO functional classification, some laboratory studies, and in most cases, preoperative right heart catheterization with or without acute vasodilator testing. Pulmonary artery catheterization with continuous hemodynamic monitoring is recommended in patients undergoing intermediate- to high-risk procedures and in patients with symptomatic PAH or a history of RV failure.

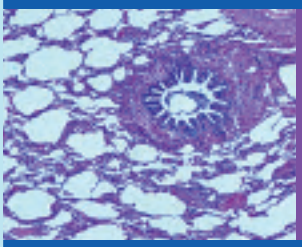
Table 2. Low- Versus High-Risk Clinical Predictors

Low-Risk Predictors
NYHA/WHO functional class I
Hemodynamics
Normal right atrial pressure (≤ 7 mmHg; off diuretics)
PVR:SVR ratio < 0.5
Mean PAP < 35 mmHg
Normal left ventricular filling pressure (PAOP 8 to 12 mmHg)
Normal cardiac output (cardiac index ≥ 2.8 L/min/m^2)
Echocardiography
Normal right atrial size
Absence of interventricular septal flattening
Absence of right ventricular hypertrophy
Right ventricular myocardial performance index < 0.75
TAPSE score ≥ 0.8 cm
Electrocardiography
Absence of right axis deviation
Laboratory
Normal serum BNP level
High-Risk Predictors
NYHA/WHO functional class III or IV
Hemodynamics
Right atrial pressure ≥ 12 mmHg
Severely elevated PAP (mean PAP ≥ 55 mmHg, PVR:SVR ratio ≥ 0.75)
Reduced cardiac output (cardiac index < 2.2 L/min/m^2)
Abnormal right ventricular stroke*work index
Echocardiography
Severe right atrial enlargement
Interventricular septal diastolic flattening
Pericardial effusion
Right ventricular myocardial performance index ≥ 0.75
Right ventricular hypertrophy
RVSP:SBP ratio ≥ 0.66
TAPSE score < 0.8 cm
Electrocardiography
Right axis deviation
Laboratory
BNP level > 330 pg/mL
Reduced creatinine clearance < 60 mL/min

BNP = B-type natriuretic protein; NYHA = New York Heart Association; PAOP = pulmonary artery occlusive pressure; PAP = pulmonary artery pressure; PVR = pulmonary vascular resistance; RVSP = right ventricular systolic pressure; SBP = systolic blood pressure; SVR = systemic vascular resistance; TAPSE = tricuspid annular systolic excursion; WHO = World Health Organization.

Table 2 lists low versus high perioperative clinical risk factors.[3,12,14-21] Although other parameters of functional capacity, such as 6-minute walk distance (6MWD) and exercise peak VO_2, are predictors of survival in patients with PAH, Ramakrishna et al found that the 6MWD did not predict early mortality associated with general surgery, possibly indicating that it may be more predictive of long-term outcome.[3,22]

A pulmonary vasodilator trial may provide additional information that can guide perioperative therapy and it has been advocated in patients with PAH undergoing general surgery.[11] There are no generally accepted criteria for a beneficial



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response. However, a drop in mPAP or PVR by at least 20% associated with an increase in cardiac output is perhaps significant (although not sufficient for identifying patients who are candidates for chronic calcium channel blocker therapy). The pulmonary vasodilators inhaled nitric oxide with FiO_2 1.0, intravenous epoprostenol, and adenosine are typically used for acute vasodilator testing. Of these, the selective pulmonary vasodilator inhaled nitric oxide is the most common agent used, and its pulmonary vasodilatory effects are typically at least as great as those of the intravenous vasodilators.[23,24]

Although acute preoperative testing with intravenous nitroglycerine and oxygen was reported to cause a greater reduction in PAP and increase in cardiac output compared with inhaled nitric oxide or nifedipine in one patient,[11] caution should be exercised when administering nonselective vasodilators in patients with PAH because of the potential development of severe systemic hypotension. It must be recognized that patients with pulmonary venous hypertension whose baseline LV filling pressures are elevated (PAOP greater than 15 mmHg) are at risk for the development of pulmonary edema if given relatively selective pulmonary vasodilators such as inhaled nitric oxide or epoprostenol, and in such cases intravenous nitroprusside, nesiritide, or nitroglycerin are more appropriate agents to reduce the LV filling pressure and PAP.

Major comorbid conditions as previously described by Eagle et al[25] can also substantially increase the risk of any surgery. A history of pulmonary embolism in particular has been associated with increased perioperative risk in patients with pulmonary hypertension undergoing noncardiac surgery.[3]

If there is baseline evidence of significant RV failure, such as markedly increased right atrial pressure and reduced cardiac output, or suprasystemic PAPs, serious consideration should be given to delaying surgery if possible until the hemodynamics can be optimized to a more acceptable level. Patients who have indicators of poor prognosis should be considered for chronic therapy with epoprostenol. Other pulmonary vasodilator therapies, such as oral endothelin receptor antagonists, phosphodiesterase type 5 inhibitors, or other prostenoids may be used as alternatives according to evidence-based guidelines[26] alone or in combination with epoprostenol

Recommendations to Anesthesiologists

In cases of elective surgery, a preoperative evaluation should be performed by an anesthesiologist and it is advisable that only anesthesiologists with experience in the care of patients with PAH should be utilized for these patients. Hemodynamic monitoring with a pulmonary artery catheter is recommended in patients undergoing intermediate- to high-risk procedures, patients with symptomatic PAH, or a history of RV failure, for both preoperative risk assessment and to guide therapy perioperatively. Although the risk of pulmonary artery catheterization in patients with pulmonary hypertension is increased because of a higher mortality associated with arrhythmias, pulmonary artery rupture, and venous air or thromboemboli, the overall risk of serious adverse events is only 1.1% with a procedure-related mortality of 0.055% in experienced hands.[27]

Table 3. Perioperative Hemodynamic Goals

Mean arterial pressure ≥ 55 to 60 mmHg
Systolic blood pressure ≥ 80 mmHg
Systemic arterial oxygen saturation 90% to 100%
Right atrial pressure < 10 mmHg
Mean pulmonary artery pressure < 35 mmHg
PVR:SVR ratio < 0.5 (if possible)
Pulmonary artery occlusion pressure 8 to 12 mmHg
Cardiac index ≥ 2.2 L/min/m^2

PVR = pulmonary vascular resistance; SVR = systemic vascular resistance.

As a guide for perioperative management, **Table 3** outlines the hemodynamic goals, which should be achieved: The cardiac output should be typically determined using the Fick equation and mixed venous oxygenation saturation measurement, because in many patients with PAH and significant tricuspid regurgitation, the cardiac output may be underestimated by the thermodilution technique.

Anesthetic induction is an unstable period, during which patients with PAH may be prone to develop systemic hypotension and cardiovascular collapse. Many different types of anesthetic agents and techniques have been used successfully in patients with PAH. However, the anesthetic technique should be chosen carefully.[6,9,28-30] The potential hemodynamic effects of anesthetic agents have been previously described in this manuscript. Although anesthetic agents do not change the PVR related to fixed pulmonary vascular disease, they can produce changes in PVR related to vascular reactivity, alterations of cardiac output and pulmonary blood flow, RV afterload, and potentially, intracardiac shunting.

Limited regional anesthesia (ie, local nerve block), which has very little hemodynamic effect, should be considered in appropriate patients, such as those undergoing minor surgery. Neuraxial regional anesthesia (eg, spinal or epidural block) can be associated with profound systemic hypotension due to the sympatholytic effects and resultant decreases in SVR in these patients with limited ability to augment RV stroke volume and cardiac output. Thus, spinal anesthesia is clearly contraindicated in most patients. On the other hand, epidural anesthesia has less systemic effects when administered carefully, and it has been used successfully in patients undergoing femoral artery repair, cholecystectomy, cesarean section, and therapeutic abortion.[9-11,31]

General anesthesia is usually needed for higher risk operations, and there is some evidence to suggest that most perioperative deaths in patients receiving general anesthesia are due to the surgical procedure and disease and not the anesthesia.[6] That being said, the hemodynamic effects of some general anesthetic agents make them either preferable or undesirable in patients with PAH. For instance, inhalational anesthetics such as nitrous oxide increase PVR and decrease contractility[32] and halothane may cause a marked reduction in contractility and increased incidence of dysrhythmias. Isoflurane, sevoflurane and desflurane may result in pulmonary vasodilation with less effect on contractility and therefore may be preferable agents in patients with PAH.[29] Intravenous anesthetics such as propofol and pentothal may also adversely affect contractility and systemic vascular resistance, causing hypotension. Ketamine appears to have little effect on systemic hemodynamics. However, there is conflicting evidence with respect to increases in PVR. Rapid-sequence etomidate induction is reported to maintain systemic hemodynamics without affecting PVR. Combination or "balanced" anesthetic techniques (eg, inhalational and intravenous or intravenous and epidural) are used frequently as a means of limiting the adverse effects of a single technique. The high-dose narcotic-oxygen technique, which can produce hemodynamic stability and pulmonary vasodilation with 100% oxygen, has been touted as the technique of choice for patients with PAH undergoing major surgery.[29,33]

Perioperative Ventilatory Management

An understanding that ventilatory management in patients receiving general anesthesia has a marked effect on PVR is important for optimal perioperative management of patients with PAH. Alveolar and pulmonary arterial hypoxia and hypercarbia are potent pulmonary vasoconstrictors and these conditions should be avoided. There is a U-shaped relationship between lung volume and PVR, with PVR being minimal at functional residual capacity and increased at both large and small lung volumes.[29] At low lung volumes, alveolar hypoxia and hypercarbia cause hypoxic pulmonary vasoconstriction, which can be improved with low levels of positive end-expiratory pressure (PEEP), resulting in a decrease in PVR.

On the other hand, high levels of PEEP (greater than 15 cm H_2O) and hyperinflation of the lungs lead to compression of the intra-alveolar vessels with marked increases in PVR. The resultant increase in RV afterload may cause or worsen RV failure and in patients with interatrial communications such as a patent foramen ovale, right-to-left shunting may occur as the right atrial pressure exceeds left atrial pressure leading to arterial oxygen desaturation. Ventilator management of the patient with PAH should therefore entail the use of high oxygen concentrations, hyperventilation to achieve a PCO_2 of 30 to 35 mmHg or less, low levels of PEEP between 5 and 10 cm H_2O, and maintenance of lung volumes at normal functional residual capacity.

Treatment of Acute Perioperative Right Ventricular Failure

Despite all precautions, acute decompensated RV failure (ADRVF) and hypotension can develop perioperatively in patients with PAH undergoing surgery. Treatment of these patients involves the reduction of RV afterload and an increase in systemic pressure. The development of RV failure is indicated by a rising RV diastolic and right atrial pressure and decreasing cardiac output. In addition to ventilatory maneuvers to reduce PVR as discussed above, pulmonary vasodilators should be administered, if needed.

The most suitable vasodilators for use in the perioperative setting to decrease PVR are the inhaled agents, which are selective to the pulmonary vascular bed and have the added poten-

tial benefit of increasing Pao_2 by reaching well-ventilated regions of the lung and improving ventilation-perfusion matching. Inhaled nitric oxide, which is typically administered at doses of 10 to 40 ppm, is the most common perioperative pulmonary vasodilator currently in use. It is rapidly inactivated by binding to hemoglobin and therefore has no systemic effects. Drawbacks to its use include the lack of response in many (approximately one third) patients, formation of potentially toxic byproducts (ie, methemoglobin, peroxynitrite, nitrogen dioxide), and the potential for rebound pulmonary hypertension with its discontinuation. Alternatively, one could use inhaled iloprost alone or in combination with inhaled nitric oxide.

Other intravenous agents available for the treatment of RV failure include nitric oxide donors (eg, nitroprusside, nitroglycerin), prostaglandins (eg, epoprostenol, prostaglandin E1, treprostinil and iloprost), and phosphodiesterase-3 inhibitor (eg, milrinone).[34,35] Intravenous epoprostenol, which has positive inotropic properties by increasing cardiomyocyte intracellular cAMP levels in addition to its effect on vascular smooth muscle, has also been used in the perioperative setting, although mostly in patients who have been receiving it as chronic therapy. Treprostinil is also typically used in patients receiving it as chronic therapy. In patients with systemic hypotension related to low cardiac output state from severe RV failure, intravenous epoprostenol and other prostaglandins may lead to an increase in blood pressure by reducing RV afterload and improving stroke volume, LV preload and cardiac output. However, there is the potential for causing worsened hypotension and/or ventilation-perfusion mismatching with arterial desaturation with all these drugs.

Inotropes, such as the beta-adrenergic agents dobutamine or dopamine, may be required to restore adequate tissue perfusion. Dobutamine is typically preferred over dopamine. However, in the setting of systemic hypotension/hypoperfusion, dopamine or norepinephrine should be considered to support RV function, improve systemic pressure, and preserve coronary perfusion. The inodilator milrinone is a phosphodiesterase-3 inhibitor that vasodilates the systemic and pulmonary vasculature and increases cardiac output. Its potent systemic vasodilatory properties can, however, overwhelm its inotropic effect and cause severe, sustained hypotension in patients with PAH, who often have mostly fixed pulmonary vascular disease. Its use should therefore be avoided in such patients. For the same reason, intravenous nitric oxide donors such as nitroprusside or nitroglycerin should not be used in acute decompensated right heart failure due to PAH as they can exacerbate systemic hypotension. The recombinant B-type natriuretic peptide nesiritide, an effective treatment of pulmonary hypertension associated with left heart failure, does not appear to decrease PVR in patients with PAH when given acutely, and because of concerns of systemic hypotension its use in PAH patients is not recommended.[36]

Perioperative Management

In general, perioperative management of the patient with PAH undergoing general surgery includes serial assessment and opti-

mization of baseline hemodynamics, the administration of chronic and acute pulmonary vasodilators in most cases, and the early identification and treatment of ADRVF and its precipitating factors. Once the baseline hemodynamics are obtained, preferably with retention of the pulmonary artery catheter in preparation for anesthesia and surgery, therapies aimed at optimizing the hemodynamics (**Table 3**) should be instituted, such as diuretics to reduce the right atrial pressure or the addition or up-titration of pulmonary vasodilators or inotropes if needed and surgery cannot be delayed.

Chronic pulmonary hypertension-specific therapies should be continued throughout the perioperative period. Arrangements should be made with the anesthesiologists and nursing staff to continue catheter-based therapies such as epoprostenol or teprostinil throughout the perioperative period. Although epoprostenol causes platelet inhibition, it typically does not cause significant bleeding with surgery. Short-term administration of digoxin may improve cardiac output and reduce sympathetic activation in patients with PAH and RV failure.[37] Patients should receive prophylaxis perioperatively to prevent deep vein thrombosis and pulmonary thromboembolism.

In patients with PAH undergoing general surgery, death when it occurs, can be sudden and often occurs in the postoperative period within the first several days. This is perhaps due to fluid shifts, increased sympathetic tone, increased pulmonary vasoconstriction, and pulmonary thromboembolism that leads to worsened RV failure, sometimes with arrhythmias.[11,30,38] In order to minimize sympathetic activation, adequate pain control should be emphasized at all times and sufficient sedation should be given in order to prevent agitation, especially while the patient is being ventilated. Sedatives with fewer negative inotropic and vasodilatory properties are preferred. Narcotic analgesics have less hemodynamic effect and may provide sufficient sedation alone. Weaning from the ventilator has been associated with paroxysms of severe pulmonary hypertension and pulseless electrical activity.[11] Extubation in a light plane of anesthesia with an inhalational anesthetic and the addition of narcotics has been advocated.[33] Selective pulmonary vasodilators, such as inhaled nitric oxide and high-flow oxygen should be used liberally if needed to manage the patient through this period.

Frequent serial examinations should be performed in order to promptly identify and treat patients who develop ADRVF. Common precipitating factors of ADRVF include dysrhythmias, infection, anemia, acidosis, hypoxia, hypothermia, and pulmonary embolism. Atrial tachyarrhythmias should be slowed with digoxin, amiodarone, or diltiazem, and amiodarone may also facilitate chemical cardioversion. If the patient is hypotensive, electrical cardioversion is indicated. The use of beta-blockers or the calcium channel blocker verapamil should be avoided because of their negative inotropic and vasodilatory that may cause hypotension. Infection is poorly tolerated in patients with PAH in whom RV contractile reserve is limited. Anemia also increases RV work and should be corrected if significant, although no evidence-based guidelines for transfusion therapy currently exist. Oxygen is a pulmonary vasodilator and maintenance of adequate oxygenation is of paramount importance in patients with PAH and RV failure. Acidemia increases PVR and therefore acidosis should be aggressively treated. In fact, small degrees of alkalemia appear to be beneficial.[40] Respiratory acidosis should be avoided (goal: $Paco_2$ 30 to 35 mmHg or less) and the prompt correction of metabolic acidosis is also indicated (goal: pH higher than 7.4). Avoidance of hypothermia and shivering is accomplished by maintenance of a body temperature around 37°C.[29]

Summary

General surgery in patients with PAH is associated with increased perioperative morbidity and mortality. Perioperative risk assessment involves an individualized approach taking into account the type of surgery as well as the hemodynamic severity of the patient's PAH, functional status, and other comorbid conditions, if any. General anesthesia is associated with higher perioperative mortality. However, this is likely related to the type of surgical procedure and severity of disease and is less often due to the anesthesia itself. A comprehensive preoperative evaluation should typically include right heart catheterization in most cases. Perioperative management must include serial assessment and optimization of hemodynamics, avoidance of factors known to cause pulmonary vasoconstriction, careful ventilatory management, administration of acute and chronic pulmonary vasodilators in most cases, and early postoperative identification and treatment of ADRVF and its precipitating factors. ■

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