

Perioperative Anesthesia Management for Pulmonary Endarterectomy: Adopting an Established European Protocol for the Asian Population

Abstract

Background: Anesthesia for pulmonary endarterectomy (PEA) has always been one of the challenges of anesthesia. As one of the leading cardiothoracic institutions in Southeast Asia, our hospital has vast interest in this subject. A local multidisciplinary team was deployed to an expert center in the United Kingdom (UK), and the experience was then integrated to the care of our patients. We present a case series of ten patients undergoing anesthesia for PEA, a first for our institution, and discuss techniques as well as potential complications. **Methods:** Patients with chronic thromboembolic pulmonary hypertension were reviewed by a multidisciplinary team, and those who were suitable for surgical intervention subsequently underwent PEA. A total of ten patients were identified and operated on. The perioperative management and conduction of anesthesia for all patients followed a protocol adapted from the expert center in the UK, with revisions to cater to our Asian population. **Results:** In the ten patients operated on, eight of them were successfully extubated on the first postoperative day. Apart from one incident of prolonged ventilator usage due to reperfusion lung injury and pneumonia, there were no major respiratory or hemodynamic complications. Certainly, six of the ten patients developed subdural hemorrhage after the commencement of enoxaparin, although none of them sustained any permanent neurological deficits. **Conclusion:** We have demonstrated that with careful planning and a well-outlined protocol, anesthesia for PEA in an Asian population can be achieved with favorable outcomes. Further fine-tuning of the protocol is still required based on local expertise.

Keywords: Anesthesia, Asian population, chronic thromboembolic pulmonary hypertension, pulmonary endarterectomy

Introduction

Anesthesia for pulmonary endarterectomy (PEA) has always been one of the challenges of anesthesia. Epidemiological studies have shown vastly different rates of chronic thromboembolic pulmonary hypertension (CTEPH) being diagnosed in an Asian versus Caucasian populations, possibly due to the lower incidences of acute pulmonary embolism in Asian populations.^[1,2] This has resulted in less operative exposure to such cases in Asian centers.^[2] With PEA being the treatment of choice for CTEPH and a rising number of such surgeries performed, it is imperative that anesthesiologists are well equipped to manage patients for surgeries with their potential complications.^[3] The prevalence of CTEPH in Singapore is currently unknown, but as one of the leading cardiothoracic

institutions in Southeast Asia, our hospital has vast interest in this subject. A local multidisciplinary team was deployed to an expert center in the United Kingdom (UK), with over 1200 operations under their belts, and the experience was then integrated to the care of our patients.^[4] We present a case series of ten patients undergoing anesthesia for PEA, a first for our institution, and discuss techniques as well as potential complications.

Methods

Patients with CTEPH were reviewed by a multidisciplinary team and those who were suitable for surgical intervention subsequently underwent PEA from November 2017 to August 2018. A total of ten patients were identified and operated on. All ten patients underwent a complete diagnostic workup including preoperative echocardiography, pulmonary angiography, right heart catheterization, isotope

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ventilation/perfusion scans, and computed tomography (CT) scan. Functional assessments such as the 6-min walk test and lung function tests were also performed. The patients selected for surgery all had Jamieson type 1 or 2 proximal disease. All ten surgeries were supervised by a senior surgeon from the UK institution. The perioperative management and conduction of anesthesia for all patients followed a protocol adapted from the expert center in UK as well, with revisions to cater to our Asian population. Preoperative and postoperative cardiac output (CO) measurements were documented. Any complications which arose during surgery and the postoperative period were also duly noted and further discussed at multidisciplinary meetings.

Case details and results

Table 1 shows a compilation of patient demographics, operative and anesthesia details, and intraoperative complications.

Table 2 shows the individual patients' preoperative and postoperative CO measurements, major postoperative complications, and length of hospital stay.

Discussion

The success of PEA surgeries is largely contingent on a multidisciplinary team-based approach. Cardiologists, respiratory physicians, cardiothoracic surgeons, perfusionists, and anesthesiologists work together to ensure optimal care before, during, and after the operations.

Specifically, anesthesia for patients undergoing PEA has always posed certain challenges to anesthesiologists. This patient population generally has a degree of right ventricular (RV) failure, and the goal of surgery is to ameliorate RV compromise as much as possible. This, however, means a certain degree of hemodynamic compromise as well as possible cardiopulmonary collapse during anesthesia. Cardiopulmonary bypass and deep hypothermic circulatory arrest (DHCA) have specific requirements with regard to cooling and cerebral protection/oxygen monitoring. Postbypass, anesthesiologists also have to be prepared to deal with potential complications such as residual pulmonary hypertension, RV failure, reperfusion pulmonary edema, and pulmonary hemorrhage.^[5,6] We discuss our technique for anesthesia adapted from the UK institution and the perioperative care of these patients.

Premedications

Patients who are on direct oral anticoagulants (DOAC) have them stopped 48 h preoperatively unless renal clearance is impaired. For patients on warfarin, it is stopped 5 days preoperatively and a therapeutic dose of enoxaparin is started 4 days preoperatively and continued till 24 h before surgery. Oral prednisolone of 1 mg/kg bodyweight is served at 2200 h night before surgery. All sedatives are avoided due to their potential for respiratory

depression with subsequent hypercarbia and acidosis leading to increased pulmonary vascular resistance (PVR). In the very anxious patient, a small dose of midazolam 0.5–1 mg is administered before setting of lines to avoid overt sympathetic activation which may also lead to increased PVR. Special consideration is paid to patients with high baseline central venous pressure (CVP) or right atrial (RA) pressures. We are considering more aggressive diuresis preoperatively to lower the RA pressures in the hope of lowering the risk of subdural hemorrhages (SDH).

Equipment, monitoring, and invasive lines

Invasive lines include a wide bore peripheral cannula, a radial 20G arterial line, a triple lumen central venous catheter, and 7 Fr swan sheath placed in the right internal jugular vein if possible. The pulmonary artery (PA) catheter is docked but not floated. Head-down position during insertion of lines is avoided. A 16G femoral arterial line is inserted by surgeons postinduction as prolonged bypass times with DHCA have been shown to dampen the radial arterial pressures.

The standard monitoring devices are applied. A transesophageal echocardiography (TEE) probe is inserted postinduction, and the PA catheter is then floated through under TEE guidance, this PA catheter is temporarily removed from the surgical field by surgeons to aid with visualization after accessing the PA (it is then repositioned before closing of the pulmonary artery). Continuous CO monitoring is obtained with CO, cardiac index (CI), PA pressures, PVR, and systemic vascular resistance (SVR) recorded. The PA catheter can be wedged at baseline to obtain the PA wedge pressure (PAWP), or alternatively and more commonly, the PAWP is assumed to be 10 mmHg in the calculation of PVR. In addition, bispectral index (BIS) and near infra-red spectroscopy are utilized for cerebral monitoring and cerebral oximetry during periods of DHCA. Esophageal and bladder (incorporated into urinary catheter) temperature probes are inserted to ensure even cooling and warming. Patients lie on both a warming mattress and underbody Bair-hugger™. ROTEM™ is available for postbypass coagulation indices if required.

Induction

Patients are induced in the operating theater with a combination of midazolam, etomidate or propofol, and fentanyl after thorough preoxygenation. An additional dose of fentanyl 500 mcg is given before sternotomy. Pancuronium is the muscle relaxant of choice. Dopamine is started at 5 mcg/kg/min, titrated, and continued for the duration of the surgery till transfer to the Intensive Care Unit (ICU). Additional inotropic agents may be prepared at the discretion of the anesthesiologist. Maintenance of adequate SVR is important as it determines the RV perfusion pressures. Boluses of phenylephrine can be administered for rapid titration of SVR.

Table 1: Patient demographics, operative and anesthesia details, and intraoperative complications

Patient	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Age (years)	45	63	55	56	67	55	55	61	52	57
Gender	Female	Female	Male	Female	Female	Female	Female	Female	Female	Male
Race	Indian	Chinese	Chinese	Chinese	Chinese	Chinese	Sikh	Indian	Chinese	Chinese
Past medical history	Anti-phospholipid syndrome DVT	HTN HLD	CTEPH	Obstructive sleep apnea	HTN HLD PUD	Endometrial polypoid tumor	HTN Left temporal-parietal infarct DVT	Diabetes HTN HLD Vogt-Koyanagi-Harada disease	HTN Asthma Dysfunctional uterine bleeding	Smoker PUD Ischemic heart disease Tabes dorsalis
NYHA class preoperation	III	II	II	III	II	I	II	II	II	II
NYHA class postoperation	I	I-II	I	I-II	I	I	II-III	II	I	I
6-min walk test preoperation (m)	319	330	460	420	354	397	90	390	481	None [†]
6-min walk test postoperation (m)	409	410	None [‡]	386	310	None [‡]	None [‡]	405	None [‡]	None [†]
Preoperative saturations on room air (%)	98	97	97	98	95	98	86	94	96	96
Postoperative saturations on room air (%)	99	97	97	99	97	98	93	98	98	100
Operation performed	PEA	PEA	PEA	PEA	PEA	PEA	PEA, CABG 1 graft*	PEA	PEA	PEA, CABG 3 grafts*
Total CBP time (min)	303	320	381	279	356	263	319	230	311	283
Total AXC time (min)	79	81	117	85	89	63	110	20	79	119
Total DHCA sessions	3	3	4	3	3	2	3	1	2	2
Length of individual DHCA sessions (min)	20, 20, 7	22, 12, 8	20, 20, 20, 9	22, 10, 18	20, 18, 20	19, 20	20, 14, 20	14	21, 21	17, 19
Surgical complications	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Anesthesia complications	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Additional inotropic support required (apart from dopamine)	None	None	None	None	None	None	None	Noradrenaline	None	None
Additional blood products required	None	None	None	None	None	None	None	None	None	None
Oral vasodilator use before PEA	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No
Oral vasodilator use after PEA	No	Yes	No	No	Yes	No	Yes	Yes	No	No

*Operation times not prolonged as CABG performed while waiting for adequate rewarming, [†]Patient's mobility was impaired by history of tabes dorsalis, [‡]6 min walk test performed usually at 3–6 months after surgery; some patients have not undergone testing yet. DVT: Deep vein thrombosis, HTN: Hypertension, HLD: Hyperlipidemia, PUD: Peptic ulcer disease, IHD: Ischemic heart disease, PEA: Pulmonary endarterectomy, NYHA: New York Heart Association, CABG: Coronary bypass graft surgery, AXC: Aortic cross-clamp, DHCA: Deep hypothermic circulatory arrest

Table 2: Individual patients' preoperative and postoperative cardiac output measurements, operative times, initiation of anticoagulation, major postoperative complications, and length of hospital stay

Patient	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Preoperative 2DE results	EF 50%, PASP 55 TAPSE 1.3	EF 58%, PASP 89 TAPSE 1.8	EF 65%, PASP 57 TAPSE 2.1	EF 72%, PASP 72 TAPSE 1.8	EF 54%, PASP 82 TAPSE 1.5	EF 69%, PASP 39 TAPSE 2.0	EF 70%, PASP 67 TAPSE 1.3	EF 65%, PASP 99 TAPSE 1.4	EF 51%, PASP 44 TAPSE 1.4	EF 53%, PASP 20 TAPSE 1.8
Postoperative 2DE results at 3-6 months	EF 54%, PASP 13 TAPSE 1.7	EF 65%, PASP 32 TAPSE 1.8	EF 67%, PASP 26 TAPSE 1.9	EF 67%, PASP 17 TAPSE 1.7	EF 62%, PASP 16 TAPSE 1.7	EF 66%, PASP 23 TAPSE 1.8	EF 65%, PASP 33 TAPSE 2.0	EF 58%, PASP 46 TAPSE 1.2	EF 48%, PASP 20 TAPSE 2.2	EF 55%, PASP 21 TAPSE 1.7
Pre-CBP cardiac output measurements	CO 4.2, CI 2.5, MAP 70, MPAP 54, CVP 22, SVR 914, SVRI 1513, PVR 838, PVRI 1387	CO 3.4, CI 2.3, MAP 2.3, MPAP 80, SVR 45, MPAP 10, SVR 1912, SVRI 1671, SVRI 3552, PVR 2457, PVR 672, 836, PVRI 1228	CO 4.5, CI 2.43, MAP 77, MPAP 115, SVR 46, CVP 7, SVR 1803, PVR 2861, SVR 1912, SVRI 1471, PVR 672, 1250, PVRI 1228	CO 3.0, CI 2, MAP 77, MPAP 49, SVR 1479, SVRI 69, 1813, SVRI 2105, SVRI 3444, PVR 711, PVRI 1211	CO 3.3, CI 2.1, MAP 76, MPAP 15, SVR 1479, SVRI 69, 1813, SVRI 2105, SVRI 3444, PVR 711, PVRI 1211	CO 3.3, CI 4.8, CI 3.1, MPAP 71, MPAP 13, SVR 3340, PVR 3085, PVR 1043, PVRI 1517	CO 3.3, CI 2.8, MAP 88, MPAP 40, CVP 7, SVR 42, CVP 14, CVP 12 SVR 1713, SVRI 3033, PVR 833, PVRI 1476	CO 2.3, CI 1.6, MAP 68, MPAP 40, CVP 7, SVR 42, CVP 14, CVP 12 SVR 1713, SVRI 3033, PVR 833, PVRI 1476	CO 3.6, CI 2.1, MAP 105, MPAP 105, MPAP 42, CVP 14, CVP 12 SVR 1713, SVRI 3033, PVR 833, PVRI 1476	CO 3.5, CI 2.0, MAP 86, MPAP 46, CVP 12 SVR 1713, SVRI 3033, PVR 833, PVRI 1476
Post-CBP cardiac output measurements	CO 4.3, CI 2.6, MAP 67, MPAP 24, CVP 9, SVR 1079, SVRI 1786, PVR 260, PVRI 431	CO 3, CI 2, MAP 76, MPAP 27, CVP 8, SVR 1813, SVRI 2666, PVR 453, PVRI 666	CO 4.7, CI 2.6, MAP 65, MPAP 64, SVR 8, SVR 1124, SVR 1783, PVR 315, PVRI 501	CO 4.1, CI 2.6, MAP 65, MPAP 26, CVP 8, SVR 1124, SVR 1783, PVR 315, PVRI 501	CO 4.0, CI 2.6, MAP 85, MPAP 37, CVP 16, SVR 1380, SVRI 2126, PVR 540, PVRI 832	CO 5.0, CI 5.4, CI 3.5, MPAP 43, MPAP 10, SVR 75, 981, SVRI 1807, PVR 26, 531, PVRI 978	CO 2.3, CI 1.6, MAP 56, MPAP 35, CVP 17, SVR 1362, SVRI 1021, SVRI 1739, PVR 289, PVRI 493	CO 4.7, CI 2.8, MAP 74, MPAP 27, CVP 14, SVR 932, SVRI 1650, PVR 253, PVRI 447	CO 5.1, CI 2.9, MAP 69, MPAP 26, CVP 10, SVR 932, SVRI 1650, PVR 253, PVRI 447	
POD 1 cardiac output measurements	CO 4.0, CI 2.3, MPAP 24	CO 3.8, CI 2.4, MPAP 26	CO 3.6, CI 2.0, MPAP 21	CO 3.9, CI 2.6, MPAP 25	CO 2.7, CI 1.8, MPAP 21	CO 4.1, CI 2.7, MPAP 23	CO 4.2, CI 2.2, MPAP 43	CO 2.5, CI 2.0, MPAP 32	CO 4.6, CI 2.7, MPAP 22	CO 3.7, CI 2.1, MPAP 25
Day of extubation	POD 1	POD 1	POD 1	POD 1	POD 1	POD 1	POD 12	POD 1	POD 1	POD 1

Contd...

Table 2: Contd...

Patient	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Initiation of enoxaparin	POD 0 (Antiphospholipid syndrome)	POD 1	POD 1	POD 1	POD 1	POD 1	POD 1	POD 1	POD 1	POD 1
Major postoperative complications	Acute SDH	Nil	Nil	Pneumothorax Atrial fibrillation	Acute-on-chronic SDH	Nil	Acute renal impairment Reperfusion lung injury Pneumonia Acute-on-chronic SDH	Accidental fall with acute-on-chronic SDH	Acute SDH	Acute SDH
Timing of SDH diagnosis	POD 4	N/A	N/A	N/A	POD 8	N/A	POD 8	POD 5	POD 7	POD 6
Symptoms of SDH	Headache	N/A	N/A	N/A	Headache	N/A	Delirium	Asymptomatic	Asymptomatic	Asymptomatic
Intervention for SDH	Burrhole and craniectomy	N/A	N/A	N/A	Conservative*	N/A	Conservative*	Conservative*	Conservative*	Conservative*
Residual neurological deficits	Nil	N/A	N/A	N/A	Nil	N/A	Nil	Nil	Nil	Nil
Length of hospital stay (days)	35	15	14	14	20	15	37	38	16	21

*Conservative management of SDH include cessation of antiplatelets and/or anticoagulation, administration of reversal such as protamine, Vitamin K, and/or fresh frozen plasma. Units: Pulmonary artery systolic pressure (mmHg), tricuspid annular plane systolic excursion (cm), cardiac output (L/min), cardiac index (L/min/m²), mean pulmonary arterial pressure (mmHg), central venous pressure (mmHg), systemic vascular resistance (dn/s/cm⁵), systemic vascular resistance index (dn/s/m²/cm⁵), pulmonary vascular resistance (dn/s/cm⁵), pulmonary vascular resistance index (dn/s/m²/cm⁵). PAWP assumed to be 10 mmHg for calculations. 2DE: Two-dimensional echocardiography, CBP: Cardiopulmonary bypass, EF: Ejection fraction; left ventricular, PASP: Pulmonary artery systolic pressure, TAPSE: Tricuspid annular plane systolic excursion, CO: Cardiac output, CI: Cardiac index, MPAP: Mean pulmonary arterial pressure, CVP: Central venous pressure, SVR: Systemic vascular resistance, SVRI: Systemic vascular resistance index, PVR: Pulmonary vascular resistance, PVRI: Pulmonary vascular resistance index, SDH: Subdural hemorrhage, POD: Postoperative day

Methylprednisolone 1 g is administered postinduction. Antibiotic prophylaxis is achieved with cefazolin 2 g or vancomycin 1 g (to run as an infusion) if the patient is methicillin-resistant *Staphylococcus aureus* positive unless otherwise indicated. A tranexamic acid bolus of 1 g is given followed by a continuous infusion of 500 mg/h maintained till ICU admission. Baseline arterial blood gas (ABG) is obtained and an insulin infusion is commenced if necessary to maintain blood sugars between 4 and 9 mg/dL. Baseline activated clotting time (ACT) is also recorded.

Ventilation is achieved with pressure control or pressure-controlled ventilation-volume guaranteed at FiO₂ of 0.3, tidal volume (TV) of 4 ml/kg, peak end-expiratory pressure (PEEP) 6 cmH₂O, and respiratory rate (RR) of 12. Care is taken to avoid hypoxia, hypercarbia, and acidosis which will further increase PVR.

Positioning

Patients are in the supine position with their hands tucked in. Overt neck extension is not recommended as it may impede cerebral perfusion. In our Asian population, due to the smaller sizes of the patients, sometimes, a shoulder roll is still required to elevate the chest for surgical exposure.

Before cardiopulmonary bypass

CO measurements are taken before initiation of CBP; these include: CO, CI, mean arterial pressure (MAP), mean PA pressure, CVP, SVR, SVR index, PVR, and PVR index, with PAWP assumed to be 10 mmHg. These measurements are repeated after patients are weaned off CBP.

Heparin of 4 IU/kg is given to patient to achieve an ACT of >400 s. The bypass pump is primed as per normal to other procedures. The only change is that the priming solution is now replaced by albumin 5% instead of crystalloids or gelafundin.

Cardiopulmonary bypass

Propofol is infused for maintenance of anesthesia at the start of CBP, titrated as per BIS monitoring. Patients with CTEPH and chronic hypoxemia are usually polycythemic. At the initiation of CBP, one to two autologous units of blood is obtained depending on the starting hemoglobin (Hb) concentration and size of the patient, targeting a hematocrit of not <22% and Hb of 7–9 g/dL during bypass. The blood is stored in OT for a maximum of 8 h and transfused back to the patient at various stages “on-pump” and when coming off bypass to reach target Hb. The hemodilution of blood with autologous donation leads to decreased blood viscosity which aids with tissue oxygen delivery and promotes uniform cooling in preparation for DHCA. In addition, autologous blood contains factors and platelets, replacing those lost and diluted by bypass.^[6] Carbon dioxide is also given at low flow during bypass to promote cerebral vasodilatation and increase cerebral oxygenation before DHCA.

Deep hypothermic circulatory arrest

Patients are cooled gradually to a core temperature of 20°C or 18° C before circulatory arrest is initiated. We use ice packs wrapped around the head with a towel instead of cooling caps for head cooling; the effects seem to be acceptable. DHCA is continued for a maximum of 20 min if cooled to 20°C, 25 min if cooled to 18°C, or when cerebral oximetry drops below 40%. Bypass is then resumed for 10 min before another round of DCHA is performed as required. Maintenance of cerebral perfusion was not employed in any of our cases as the PEACOG trial performed at an expert center showed no significant impairment in cognitive function between antegrade cerebral perfusion and DHCA, and DHCA is recommended as the optimum modality.^[7]

Rewarming

Rewarming is achieved gradually to ensure uniformity. Esophageal temperatures should not exceed 37°C and the gradient between esophageal and bladder temperatures should not exceed 5° at any point. Ice packs are removed from the head together with the change of jelly doughnut head rings as they tend to remain cold. Ventilation is resumed initially at FiO₂ of 0.25–0.3, TV 4–5 ml/kg, PEEP of 6, and RR 12 with an ICU ventilator. TVs are adjusted to 8 ml/kg, and FiO₂ increased to 0.6%–0.8% when weaning off bypass. ABGs are repeated to ensure normal pH and electrolyte balances, with serum potassium targeted at no <5 mmol/L. Atrial-ventricular pacing is usually commenced at a rate of 80–90 beats/min if required to maintain CO. The aim is to wean off bypass with the patient relatively underfilled: CVP half of prebypass values.

After cardiopulmonary bypass

Additional inotropic support may be started if required, usually adrenaline or noradrenaline. The postbypass CO measurements are recorded again. Should the MAP be borderline when coming off bypass, CO should be guided by cerebral oximetry as a surrogate marker instead of MAP, aiming for levels obtained when on full flow on bypass. Once the patient is hemodynamically stable, protamine is administered to achieve prebypass values. A target Hb of 10 g/dL is desired, additional donor blood may be required. Rotem™ is performed after reversal with protamine to guide with the replacement of blood products if there is a question of coagulopathy. RR is adjusted to achieve normocapnia. As much as possible, no additional opiates are administered.

After surgery

Patients are transferred to the ICU with the ICU ventilator and last ventilator setup in OT. This is to avoid disconnecting the endotracheal tube from the ventilator to maintain PEEP as these patients are prone to reperfusion lung injury. Dopamine infusion is typically continued overnight to maintain CI and perfusion pressures at appropriate levels. Pacing is continued from OT if needed. The PA catheter position is checked, and the balloon inflation device disabled to prevent further use in ICU. Mean PA pressure, CO, and CI are documented till the first postoperative day. Patients are kept intubated overnight for lung protection with the aim for extubation after 24 h. Fluids are kept at a minimum to maintain “dry lungs,” with the aim of a negative 1–1.5 L fluid balance by the first postoperative day. Prophylactic enoxaparin is started at 40 mg/day (dose adjustment needed for renal impairment) 24 h after surgery if bleeding is <25 ml/h for two consecutive hours. This is escalated to a therapeutic dose of enoxaparin at 0.75 mg/kg twice a day (dose adjustment needed for renal impairment) 48–72 h postsurgery if there are no contraindications. Warfarin may be resumed with enoxaparin overlap if there are no contraindications; usually after the postoperative day 2. For those previously on DOAC, this can be resumed the morning or evening before discharge (depending on the frequency of dosing). The enoxaparin is to be discontinued once DOAC is commenced.

Complications

Three major complications associated with PEA are pulmonary hemorrhage, reperfusion pulmonary edema, and residual pulmonary hypertension with RV failure.^[5,6,8] Only one out of the ten patients operated on suffered from such complications in this case series, but we briefly discuss the planned management should such issues arise.

Pulmonary hemorrhage, if detected intraoperatively, can be repaired primarily if surgery is possible. Depending on the severity of bleed, conservative management

consisting of PEEP, lung isolation of segment bleeding with bronchial blockade, reversal of heparin, application of a topical vasoconstrictor (vasopressin or phenylephrine), and correction of coagulopathies is also an alternative if the bleed is small.^[9] If surgical access is difficult, and the surgical field is obstructed by bleeding, lung isolation strategies may be insufficient. Bypass is resumed to reduce PA blood flow and bleeding and then switched to central venous-arterial extracorporeal membrane oxygenation (ECMO) should RV function be compromised or venous-venous ECMO if biventricular function is preserved. Heparin is fully reversed with protamine, and the patient is brought to the ICU with chest open and central ECMO *in situ*.^[6,9] Heparin is withheld for the first 24 h.^[10] After 24–48 h, a bronchoscopy is performed to assess for bleeding. Should the bleeding abate, ECMO is weaned off and the chest is then closed. Lung isolation may be used in conjunction with ECMO to prevent bleeding into other lung segments.

Reperfusion pulmonary edema is one of the most common complication after pulmonary endarterectomies and typically occurs within 48-h postsurgery.^[11] It is characterized by high permeability edema and new radiological opacities in areas of the lungs that have been reperfused.^[12,13] Prevention starts with protective lung strategies; (1) protective lung ventilation with reduced TVs and maintenance of PEEP and (2) maintenance of “dry lungs” by minimizing fluid overload, coming off bypass with a low CVP. For management of reperfusion pulmonary edema, the treatment is mainly supportive with diuresis, minimizing FiO₂, and avoidance of high CO.^[5,6] In refractory cases, ECMO can be initiated and may be lifesaving.^[14]

Residual pulmonary hypertension may present with concurrent RV failure and failure to wean off CBP. These patients often require inotropic support and attention is paid to optimizing RV preload.^[6,8,15] They may have to be commenced on ECMO if the hemodynamics are unstable.^[15] Pharmacological therapy may be helpful in some cases. Inhaled nitric oxide or iloprost will help to reduce PVR.^[16-18] If the residual pulmonary hypertension is significant, pulmonary antihypertensive agents such as prostacyclin analogs and phosphodiesterase-5 inhibitors should be continued.^[6,8,19]

For our institution, the most common complication seems to be SDH with 60% of patients affected. Subdural hemorrhage is one of the less common, but potential complications after PEA surgery. Current literature yields little on its incidence; a study conducted by Papworth Hospital from 2000 to 2013 showed that 6 out of 42 patients (14%) undergoing PEA for CTEPH sustained SDH.^[4] In comparison, our complication rate is fourfold despite adherence to protocol. Several postulations have been made with regard to this increased rate. First, to maintain “dry lungs” in the postoperative

period, patients are diuresed aggressively (from mannitol in the pump solution and mannitol and frusemide given postoperatively), causing rapid fluid shifts. Second, DHCA with subsequent rewarming causes marked changes in cerebral perfusion with repeated vasoconstrictive, then vasodilatory episodes. A combination of these two factors, together with reduced RV afterload and improved CO, may lead to increased shearing forces between bridging veins of the two meningeal layers, resulting in SDH. Another factor could be that Asians are more prone to development of intracranial bleeds as compared to the Western population.^[20,21] As half of the patients who sustained SDH did not have overt neurological symptoms (three out of six), there is a possibility that rates of SDH after PEA could have been underreported previously. Our institution is currently looking at several strategies toward prevention, these include: (1) More aggressive preoperative diuresis for patients with baseline high CVP/RA pressures to lower them, (2) Gentler postoperative diuresis, (3) routine screening with postoperative CT brains and resumption of anticoagulation only if there is no evidence of intracranial bleeds.

Conclusion

This case series is a first of its kind for our hospital. In the ten patients operated on, eight of them were successfully extubated on the first postoperative day. Apart from one incident of prolonged ventilator usage due to reperfusion lung injury and pneumonia, there were no major respiratory or hemodynamic complications. Certainly, six of the ten patients developed SDH after the commencement of enoxaparin. Only one of them required surgical intervention, the rest were managed conservatively. All cases of SDH were promptly picked up and none of the patients sustained any permanent neurological deficits. We are presently in the midst of revising our protocol as mentioned above in the hope of decreasing such incidences.

In this series, we have demonstrated that with careful planning and a well-outlined protocol, anesthesia for PEA in an Asian population can be achieved with favorable outcomes. There are definitely variations due to different patient demographics and further fine-tuning of the protocol is still required based on local expertise. Although this surgery is associated with a high risk of mortality and morbidity, with increased experience and further research, we hope to achieve higher success rates and promote awareness around the region.

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Conflicts of interest

There are no conflicts of interest.

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