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CURRENT OPINION

Role of extracorporeal membrane oxygenation and surgical embolectomy in acute pulmonary embolism

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Purpose of review

Surgery is an important option to consider in patients with massive and submassive pulmonary emboli. Earlier intervention, better patient selection, improved surgical techniques and the use of veno-arterial extracorporeal membrane oxygenation (VA ECMO) have contributed to improve the safety of surgery for pulmonary emboli.

Recent findings

VA ECMO is rapidly changing the initial management of patients with massive pulmonary emboli, providing an opportunity for stabilization and optimization before intervention. The early and long-term consequences of acute pulmonary emboli are better understood, in particular with regard to the risks of chronic thromboembolic pulmonary hypertension (CTEPH), an entity that should be identified in the acute setting as much as possible. The presence of chronic thromboembolic pulmonary disease can be associated with persistent haemodynamic instability despite removal of the acute thrombi, particularly if pulmonary hypertension is established. The pulmonary embolism response team (PERT) is an important component in the management of massive and submassive acute pulmonary emboli to determine the best treatment options for each patient depending on their clinical presentation.

Summary

Three types of surgery can be performed for pulmonary emboli depending on the extent and degree of organization of the thrombi (pulmonary embolectomy, pulmonary thrombo-embolectomy and pulmonary thrombo-endarterectomy). Other treatment options in the context of acute pulmonary emboli include thrombolysis and catheter-directed embolectomy. Future research should determine how best to integrate VA ECMO as a bridging strategy to recovery or intervention in the treatment algorithm of patients with acute massive pulmonary emboli.

Keywords

complications, chronic thromboembolic disease, chronic thromboembolic pulmonary hypertension, pulmonary emboli, surgery

INTRODUCTION

Acute pulmonary embolism is a major health problem, representing the third most common cause of cardiovascular mortality after myocardial infarction and stroke [1]. The management of acute pulmonary embolism has changed over the past 20 years, with the recognition that surgical embolectomy was an important treatment option for massive and submassive acute pulmonary embolism and, more recently, with the implementation of veno-arterial extracorporeal membrane oxygenation (VA ECMO) as a bridging strategy to recovery or intervention in the context of acute pulmonary embolism. The early and long-term consequences of acute pulmonary embolism are also better understood, in particular with regard to the risks of chronic thromboembolic pulmonary hypertension (CTEPH).

Three types of surgery can be performed for pulmonary emboli: Pulmonary embolectomy in the presence of an acute massive pulmonary

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KEY POINTS

- Surgical embolectomy is an important treatment option for massive and submassive acute pulmonary emboli.
- Identification of patients at high risk of haemodynamic compromise and early intervention is an important component for the success of surgical embolectomy.
- Evidence of underlying chronic thromboembolic pulmonary disease is important to identify, as removing the fresh thrombi can be associated with persistent haemodynamic difficulty.
- Veno-arterial extracorporeal membrane oxygenation as a bridge to decision and intervention in massive pulmonary emboli and as a bridge to recovery after surgery has become an integral part of the management of patients with acute and chronic thromboembolic disease.

embolism with fresh floating clot in the lumen of the pulmonary artery, Pulmonary thrombo-embolectomy in the presence of subacute massive pulmonary embolism with semi-organized thrombi on the wall of the pulmonary artery, and Pulmonary thrombo-endarterectomy (PTE) in the presence of chronic disease with organized thrombi along the wall of the pulmonary artery (Fig. 1). Apart from surgery, other treatment options in the context of acute pulmonary embolism include thrombolysis (either systemic or catheter-directed) and catheter-directed embolectomy. The treatment option should be adapted to each patient presenting with acute pulmonary embolism. The pulmonary embolism response team (PERT) is an important component in the management of massive and submassive acute pulmonary embolism to adapt the decision based on the patient's clinical presentation and team's expertise.

HISTORY OF SURGICAL EMBOLECTOMY

The history of surgical embolectomy for acute pulmonary embolism dates back to Frederic Trendelenburg who was the first to attempt this procedure in 1908 in Leipzig, Germany, after experimenting this approach in animals [2]. Following rapid exposure of the pulmonary artery via a left parasternal approach, the proximal aorta and the main pulmonary were encircled through the transverse sinus of the pericardium. Both vessels were then occluded by traction of the encircling band, the conus pulmonalis was incised and the acute clot extracted. This procedure was performed in patients who collapsed from acute pulmonary embolism. The first two patients reported by Trendelenburg died 15 and 37 h after the surgery [2,3]. Martin Kirschner, Trendelenburg's student, reported the first patient who fully recovered after pulmonary embolectomy in 1924 using this approach [4]. During the next decade, only three more successes were documented [5]. In 1937, John Gibbon estimated that only nine out of 142 patients who underwent this procedure were discharged from hospital alive [6].

While working under the supervision of Edward Churchill at the Massachusetts General Hospital, John Gibbon was exposed to a patient who underwent a Trendelenburg operation for massive pulmonary embolism [7]. Due to the high risk of this operation, the patient was monitored, and the Trendelenburg operation carried out only when the patient's 'respirations ceased and blood pressure could not be obtained'. The patient did not survive. This experience encouraged John Gibbon to perform a series of experiments in the research laboratory at the Massachusetts General Hospital to characterize the clinical presentation of acute pulmonary embolism, and to start working on a machine to oxygenate the blood and maintain the circulation, which led to the development of cardiopulmonary bypass.

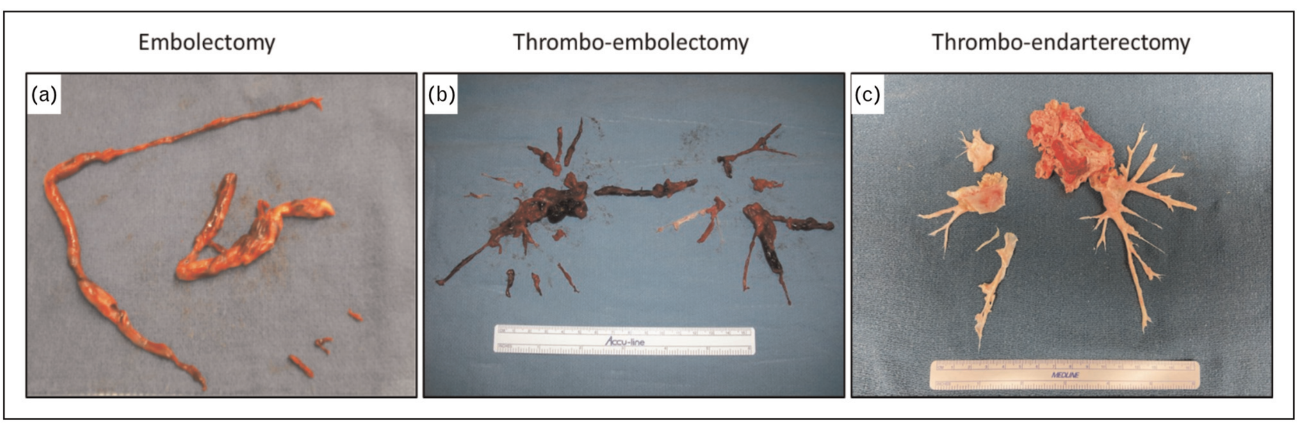

FIGURE 1. Three types of surgery can be performed for pulmonary emboli. (a) Pulmonary embolectomy. (b) Pulmonary thrombo-embolectomy. (c) Pulmonary thrombo-endarterectomy.

Following the work from Philippe Richet who described two mode of clinical presentation with massive pulmonary embolism, the 'syncopale type' and the 'asphyxique type' [8], Gibbon demonstrated in animals that the syncopale type was due to an acute occlusion of at least 60% the main pulmonary artery associated with a rapid drop in blood pressure, while the asphyxique type was due to an occlusion of the lobar branches of the pulmonary artery associated with hypoxemia rather than hypotension [9].

Twenty-two years after his exposure to the Trendelenburg operation, John Gibbon carried out the first successful operation using cardiopulmonary bypass on 6 May 1953 to close an atrial septa defect [7]. Sharp [10] was the first to report a pulmonary embolectomy using cardiopulmonary bypass in 1962. Despite the use of cardiopulmonary bypass, pulmonary embolectomy remained a salvage procedure performed in patients undergoing cardiopulmonary resuscitation or severely compromised haemodynamically. The mortality from this approach, therefore, remained high around 30–50% until the end of the twentieth century when pulmonary embolectomy started to be offered to patients with submassive acute pulmonary embolism rather than in extremis [11]. Earlier intervention and more selective indications led to a reduction in the operative mortality to 10% or less after pulmonary embolectomy [12]. These results demonstrated that the identification of patients at a high risk of haemodynamic compromise and early intervention was an important component for the success of surgical embolectomy.

INDICATIONS FOR SURGICAL EMBOLECTOMY

Surgical embolectomy is considered after failure of thrombolysis or when thrombolysis is contraindicated in the context of high-risk pulmonary embolism defined by hypotension and haemodynamic shock [13,14]. Surgical embolectomy can also selectively be performed in the presence of an intermediate-high risk pulmonary embolism defined by evidence of right heart strain on imaging combined with abnormal troponins despite the absence of haemodynamic instability [12].

The presence of a clot in transit in the right atrium or right ventricle is another indication for surgery [15]. Clot in transit can lead to paradoxical embolus in the context of a patent foramen ovale (PFO), acute haemodynamic collapse due to migration of the clot in the pulmonary artery or obstruction of the right ventricular outflow tract (Fig. 2).

Caveats in surgical embolectomy

Chronic pulmonary embolism in the acute setting

The concept of acute on chronic pulmonary embolism is an entity that is increasingly recognized and important to look for in the acute setting. This concept emerged from studies in the CTEPH population. The International CTEPH registry demonstrated that up to 41% of the patients with CTEPH had a history of acute massive pulmonary embolism and 14% of them required thrombolysis [16]. In a

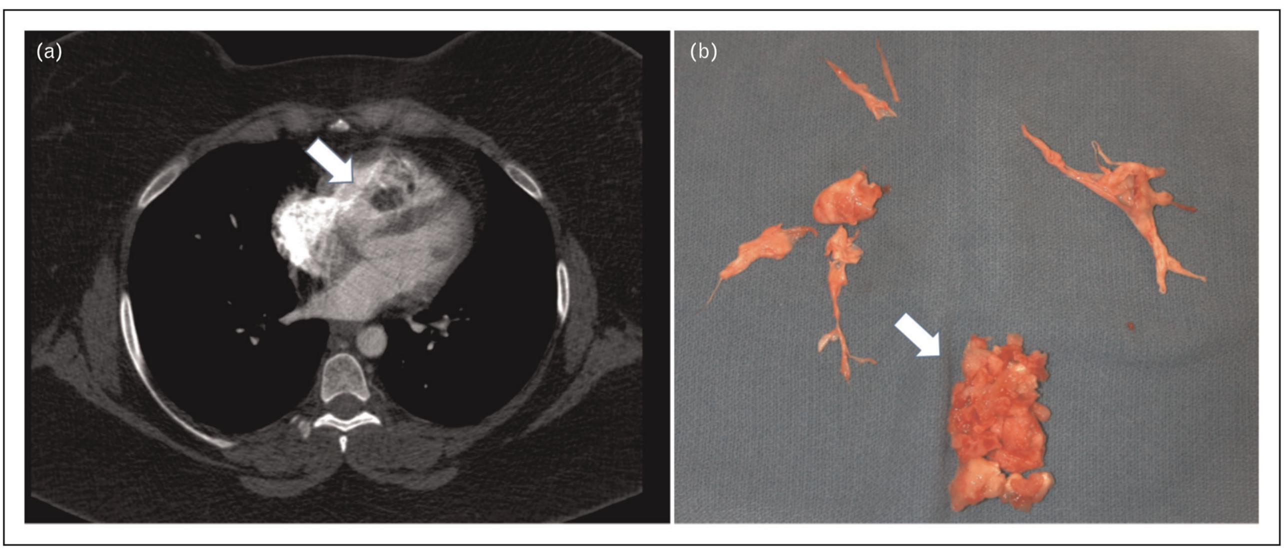

FIGURE 2. Patients presenting with acute haemodynamic shock due to an organized clot in transit obstructing the right ventricular outflow tract. (a) CT scan demonstrates the clot in the right ventricle (arrow). (b) Pulmonary thrombo-endarterectomy was performed with resection of the organized thrombi in the right ventricle (arrow).

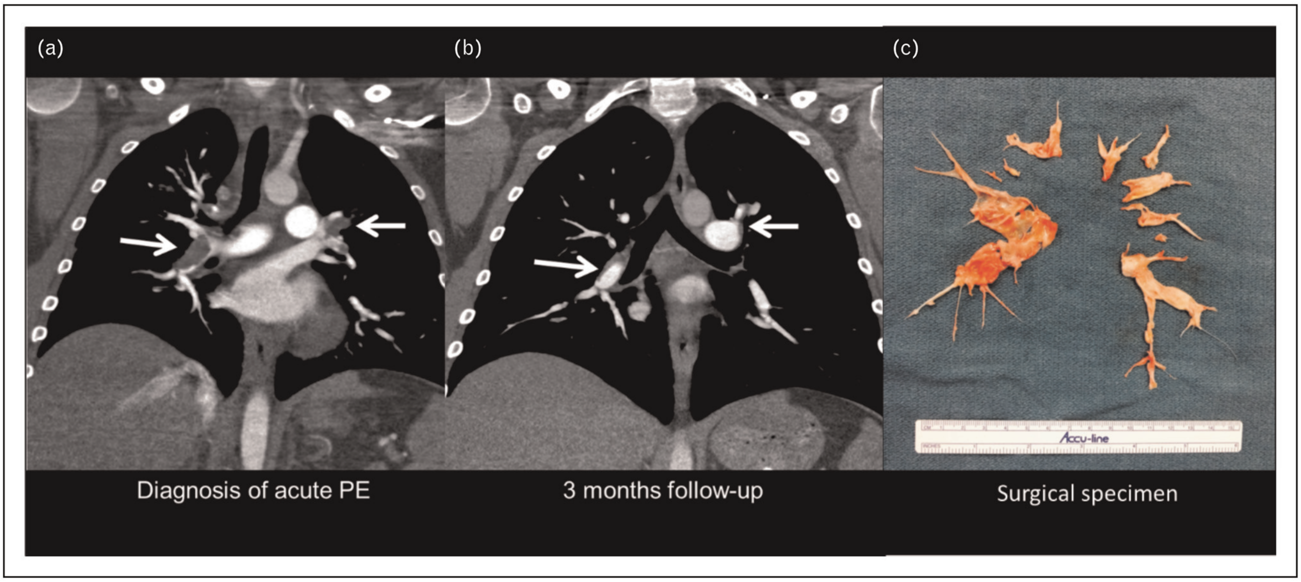

FIGURE 3. Patients presenting with submassive pulmonary emboli and acute on chronic pulmonary embolism. (a) CT scan on initial presentation demonstrates acute pulmonary emboli along the descending branch of the right pulmonary artery. (b) After 3 months of anticoagulation, the clot burden has decreased, but the chronic component of the disease remains present and pulmonary hypertension was documented on right heart catheterization. (c) Pulmonary thrombo-endarterectomy was performed.

prospective clinical trial, Guérin *et al.* [17] observed that 5% of the patients presenting with acute pulmonary embolism had CTEPH at the time of the acute presentation and that evidence of chronic disease could frequently be detected on the index computed tomography (CT) in the acute setting.

A diagnosis of CTEPH should be suspected in the acute setting by the presence of long-standing shortness of breath, large clot burden on CT scan and evidence of pulmonary hypertension on echocardiogram [18]. These patients are frequently haemodynamically stable despite an impressive extent of thromboembolic material on the CT pulmonary angiogram (CTPA) due to the chronic adaptation of the right ventricle. The presence of mosaic lung attenuation, extensive bronchial circulation, organized clot on the wall of the pulmonary artery and evidence of webs and bands on CTPA in the context of an acute pulmonary embolism are highly suggestive of chronic thromboembolic pulmonary disease [17].

Evidence of underlying chronic thromboembolic pulmonary disease is particularly important to identify if surgical embolectomy is contemplated, as removing the fresh thrombi only will leave the residual chronic disease in place with potentially major haemodynamic difficulty postoperatively, particularly if pulmonary hypertension is already established. PTE surgery is the preferred operation for these patients. Therefore, patients with evidence of chronic thromboembolic pulmonary disease should be transferred to centre with an expertise in PTE surgery either urgently in the presence of haemodynamic instability or during follow-up if they are stable. These patients will require further investigations to confirm the diagnosis of CTEPH. These investigations are generally conducted after 3 months of anticoagulation in haemodynamically stable patients to ensure that the acute component of the disease is resolved (Fig. 3).

Subacute massive pulmonary embolism

Subacute massive pulmonary embolism is a rare entity that typically is associated with shortness of breath of at least 2 weeks duration before the diagnosis of acute pulmonary embolism [19]. These patients can present with severe hypoxemia in the absence of haemodynamic instability. Generally, this condition can be treated conservatively with anticoagulation alone. However, persistent severe hypoxemia may require intervention such as surgical thrombo-embolectomy or catheter-directed embolectomy (Fig. 4). Thrombolytic therapy is also an option, but the benefit can be limited, as the old thrombus contains less plasminogen [20].

The distinction between submassive and chronic pulmonary embolism can be difficult on imaging (Fig. 4). However, evidence of pulmonary hypertension on echocardiogram or on right heart catheterization strongly suggest a diagnosis of CTEPH rather than subacute massive pulmonary embolism [19]. Despite the absence of pulmonary hypertension, patients with subacute pulmonary embolism may also be at risk of residual symptoms and benefit from reassessment after 3 months of antiocoagulation [21].

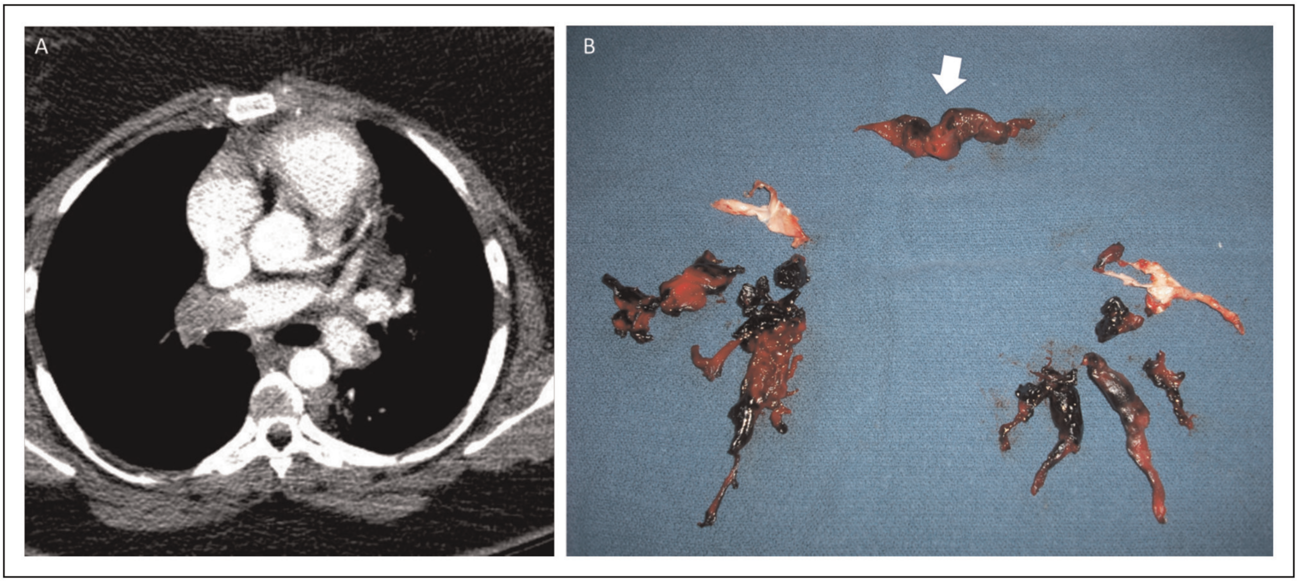

FIGURE 4. Patient haemodynamically stable presenting with severe hypoxemia and a clot in transit through a patent foramen ovale. (a) The CT scan demonstrated pulmonary emboli in the right pulmonary artery. (b) Resection of the clot in transit (arrow) on cardiopulmonary bypass after cross-clamping the aorta with removal of the fresh and organized thromboembolic material in the right and left pulmonary artery using periods of circulatory arrest at 20°C–24°C.

Sarcoma of the pulmonary artery

On rare occasion, an intimal sarcoma of the pulmonary artery can present as acute massive pulmonary embolism and may require emergency surgery (Fig. 5). Intimal sarcoma of the pulmonary artery is characterized by disease extending to the pulmonary valve and right ventricular outflow tract. Hence, features suggesting of sarcoma on imaging include extensive disease in the main pulmonary artery with abnormalities on the pulmonary valve. The treatment for intimal sarcoma of the pulmonary artery is PTE surgery if the disease is limited within the lumen of the pulmonary artery. A tissue diagnosis can be challenging to obtain and is thus generally not required preoperatively.

SURGICAL TECHNIQUE

The diagnosis of acute massive pulmonary embolism should be confirmed by CTPA or echocardiogram before proceeding with surgery. A transesophageal echocardiogram (TEE) can be done in the operating

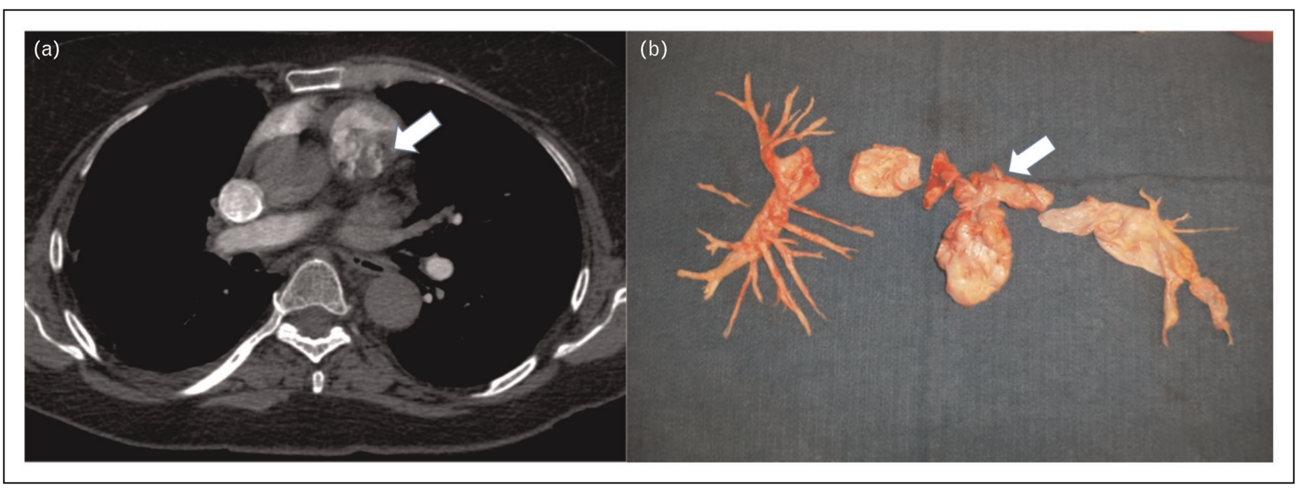

FIGURE 5. Patient presenting with haemodynamic instability in the context of acute pulmonary embolism. (a) Calcification at the level of the pulmonary valve (arrow) suggest the possibility of intimal sarcoma of the pulmonary artery. (b) Urgent surgery was performed with resection of the pulmonary valve (arrow) and reconstruction using a bioprosthesis as well as endarterectomy of the pulmonary arterial tree on the right and left side.

room before proceeding with surgery if a bedside transthoracic echocardiogram or CTPA was not possible. The TEE will also be helpful to rule out a clot in transit in the right atrium or right ventricle.

If the patient is awake, but haemodynamically compromised, prepping and draping the patient before induction of anaesthesia and intubation will be important due to the risk of haemodynamic collapse. A median sternotomy is then rapidly performed and the pericardium opened. The ascending aorta and both vena cava are cannulated through the right atrium after full heparinization. In the absence of a clot in transit or intra-cardiac anomaly, aortic cross-clamp is not necessary. Both the inferior and superior vena cava are snared over the single venous cannula. The main pulmonary artery can be opened over 2–3 cm beyond the pulmonary valve and extended to the left pulmonary artery. The clot can then be suctioned from the left and right pulmonary artery using a large bore suction catheter. Additional thrombectomy can then be done under direct vision with a forceps. The right pulmonary artery can also be opened between the aorta and the superior vena cava for better visualization of the extent of disease on the right side. Extreme care should be taken to avoid any damage to the wall of the pulmonary artery using the forceps. The pulmonary artery can be inspected to see if there are any significant residual thrombi present at the lobar and segmental level. In the presence of an acute pulmonary embolism, the embolectomy is generally sufficient to reperfuse the lungs and unload the right heart. The pulmonary artery is then closed with two running sutures of 5-0 prolene and the patients wean off cardiopulmonary bypass. An inferior vena cava filter can be inserted intraoperatively or postoperatively.

In the presence of extensive residual semi-organized thrombi along the wall of the artery at the lobar and segmental level, the embolectomy may not be sufficient, and a more extensive thrombo-embolectomy may be required under direct vision. Thrombo-embolectomy can be challenging due to the poor visibility with a beating heart and the backflow from the bronchial circulation. In these situations, cooling the patient for a short period of circulatory arrest and aortic cross-clamping may be necessary to obtain adequate visibility when dissecting the semi-organized thrombi from the wall of the pulmonary artery. The right pulmonary artery will also need to be dissected from behind the aorta and the superior vena cava to be able to adequately open the right pulmonary artery. The degree of cooling can range between 20°C and 24°C depending on the extent of organized and semi-organized disease and the duration of anticipated circulatory arrest. In the presence of chronic disease, deep hypothermia at 20°C is necessary to perform a complete thrombo-endarterectomy down to the segmental branches with circulatory arrest of up to 20 min.

Role of veno-arterial extracorporeal membrane oxygenation

Veno-arterial extracorporeal membrane oxygenation as a bridge to recovery after surgery

Complications after pulmonary embolism surgery include right heart failure, pulmonary oedema and haemoptysis. Nitric oxide can be helpful to facilitate weaning from cardiopulmonary bypass and optimize oxygenation. However, in the presence of major difficulties, VA ECMO is generally the best option. VA ECMO can be initiated peripherally using the femoral vessels, or centrally through the sternotomy [22,23▪]. Peripheral VA ECMO allows chest closure [22]. However, central VA ECMO has the advantage to avoid dissecting a new surgical site, facilitate the drainage from the right heart and avoid the risk of harlequin syndrome [23▪]. The postoperative management of VA ECMO requires careful haemodynamic monitoring to ensure that there is ongoing pulsatile flow through the pulmonary artery. In general, the situation improves over a period of 2 or 3 days allowing central VA ECMO to be weaned and the chest closed. If gas exchange remains a problem, veno-venous ECMO can be started to facilitate weaning from central VA ECMO and allow chest closure.

Veno-arterial extracorporeal membrane oxygenation as a bridge to decision and intervention in massive pulmonary embolism

In addition to its role as a bridge to recovery after pulmonary embolism surgery, VA ECMO has had an increasing role in the management of massive pulmonary embolism as a bridge to decision and possible intervention. Increasing experience demonstrates that peripheral VA ECMO is an excellent option to resuscitate patients with haemodynamic instability in the context of an acute massive pulmonary embolism [24▪▪]. Peripheral VA ECMO can be inserted under local anaesthesia, which provide additional safety by avoiding intubation and positive pressure ventilation. VA ECMO does also provide the benefit to temporize the situation and stabilize patients in haemodynamic shock before deciding on further interventions such as thrombolysis, surgical embolectomy or catheter-directed embolectomy [25]. The literature does not clearly suggest the advantage of one option over another [26]. However, surgical embolectomy or catheter-directed embolectomy can be particularly beneficial in patients with extensive clot burden to facilitate VA ECMO weaning [27]. VA ECMO does also offer the opportunity to assess the patient's trajectory before making a decision. In our experience, catheter-directed thrombectomy has been an excellent option for some patients with massive pulmonary embolism once they are stabilized on VA ECMO. Survivors from VA ECMO in the context of cardiogenic shock from massive pulmonary embolism can experience good recovery in the long-term with only minor cardiopulmonary limitations [28]. Although extremely encouraging, prospective studies will be required to determine the role of VA ECMO in the management of acute massive pulmonary embolism, including the value of VA ECMO in pulseless electrical arrest, and identify factors of success for outcome [29■■,30].

CONCLUSION

Surgery for acute pulmonary embolism is an important option to consider in patients with massive and submassive pulmonary embolism. Earlier intervention, better patient selection, improved surgical techniques and the use of VA ECMO have contributed to improve the safety of surgery for pulmonary embolism. VA ECMO is also rapidly changing the initial management of patients with massive pulmonary embolism, providing an opportunity for stabilization and optimization before intervention.

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Conflicts of interest

M.D.P. has received honoraria from Actelion, AstraZeneca, Bayer, Bristol Myers Squibb, Merck and Roche, outside of the submitted work.

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