Catheter-based techniques for pulmonary embolism treatment

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ABSTRACT

Pulmonary embolism (PE) is a life-threatening condition characterised by occlusion of the pulmonary vasculature, with a global incidence of approximately 1 in 1,000 patients. While pharmacological therapy remains the cornerstone of PE management, selected patients may benefit from catheter-directed treatments due to their potential for rapid symptom relief and swift haemodynamic stabilisation. Catheter-directed thrombolysis and catheter-directed mechanical thrombectomy are current treatment options, though their availability is still limited. This review provides a practical outlook on catheter-directed therapies for PE, outlining optimal procedural planning, device selection, technical execution, evaluation of results, and management of complications.

Pulmonary embolism (PE) is a life-threatening condition with a heterogeneous clinical presentation, ranging from asymptomatic cases to cardiac arrest, with up to 50% mortality at 90 days[1]. While most patients are managed with anticoagulation alone, high-risk cases require reperfusion therapy[2]. Systemic thrombolysis, despite limited evidence from randomised controlled trials[3,4], remains the guideline-recommended strategy for high-risk patients[5-7] but is underutilised because of bleeding concerns[8,9]. Surgical embolectomy, in contrast, is less widely available and carries high postprocedural mortality rates[5,9-12]. Consequently, less invasive catheter-directed treatments are emerging, divided into two main approaches: catheter-directed thrombolysis (CDT), using low-dose thrombolytics through a small-bore catheter, and catheter-directed mechanical thrombectomy (CDMT), using a medium- to large-bore catheter to mechanically remove the thrombus. Due to limited evidence supporting the safety and efficacy of these techniques[13], an individualised approach is essential to maximise the benefit and minimise the risks of these interventions. This review offers a practical guide to transcatheter PE treatment, focusing on procedural planning, device selection, technical execution, and outcome evaluation with the devices presently in use.

Procedural planning

RISK ASSESSMENT AND THROMBUS LOCALISATION

Prior to the procedure, it is essential to assess the clinical presentation[14] and haemodynamic status, and perform imaging to evaluate patient risk, detect early signs of deterioration, and optimise the strategy and timing of the intervention **(Figure 1)**.

ULTRASOUND

A preprocedural transthoracic echocardiogram (TTE) provides critical insights into right ventricular (RV) dysfunction, a major determinant of outcomes. TTE can also detect a clot in transit, raising the risk of paradoxical embolism through a patent foramen ovale (PFO) – a key piece of information for guiding treatment decisions. It can also reveal significant right-to-left shunting through a PFO, potentially worsening oxygenation. Furthermore, Doppler ultrasound of the lower extremities aids in assessing deep vein thrombosis and access site selection.

Figure 1. *Clinical, haemodynamic, and imaging features for pre- and postprocedural monitoring. In the preprocedural phase, assessing these elements helps to evaluate patients' clinical risk, identify signs of potential clinical deterioration, and inform decision-making regarding appropriate interventions. In the postprocedural phase, monitoring improvements in these same parameters provides information regarding treatment efficacy and guides further therapeutic strategies. *In the setting of right heart catheterisation during pulmonary embolism, the evaluation of total pulmonary resistance, as the ratio of mean pulmonary artery pressure (mPAP) to cardiac output (CO), may be preferred over pulmonary vascular resistance, which is calculated as the difference between mPAP and pulmonary capillary wedge pressure divided by CO, as pulmonary artery wedging can be challenging due to extensive thrombus distribution obstructing the pulmonary vasculature. Down arrows represent that a reduction in this element is a marker of deterioration; up arrows represent that an increase in the element is a marker of deterioration; the plus symbol represents that if this specific therapy is necessary, it is a marker of deterioration. bpm: beats per minute; Diast: diastolic; LV: left ventricular; O2: oxygen; rpm: respirations per minute; RV: right ventricular; sO2: oxygen saturation; SP: systolic pressure; TAPSE: tricuspid annular plane systolic excursion; WU: Wood units*

COMPUTED TOMOGRAPHY

Computed tomography (CT) scanning is essential for PE diagnosis and procedural planning[5], providing detailed information on thrombus location and anatomical challenges for catheterisation (e.g., a wide main pulmonary artery [MPA] bifurcation angle, a subacute or chronic thrombus adhering to the vessel walls). Understanding vascular anatomy is crucial for correlating preprocedural and angiographic images and ensuring safe distal navigation during the procedure **(Supplementary Figure 1)**. Extending the scan to abdominal and proximal lower limb segments helps exclude peripheral vein thrombosis to ensure safe vascular access. CT may also distinguish between acute and chronic PE, which is useful as chronic forms significantly influence the procedural approach and can impact outcomes **(Supplementary Table 1)**.

RIGHT HEART CATHETERISATION

Information from right heart catheterisation is instrumental in assessing the pre- and postprocedural haemodynamic status **(Figure 1)**.

PULMONARY ANGIOGRAPHY

A preprocedural CT scan alone, especially with coronal reconstructions, is sufficient to plan and successfully guide the interventional procedure in most cases, thus avoiding multiple selective angiograms that could potentially destabilise the patient. However, selective pulmonary angiography may be necessary to re-evaluate the thrombus distribution before intervention if changes caused by medical therapy are expected (e.g., thrombolysis after CT or a long delay between CT and intervention). During pulmonary angiography, 10-20 ml of contrast is usually administered at 3-8 ml/s in the anteroposterior position for MPA and 30-40° homolateral oblique views for the right pulmonary artery and the left pulmonary artery. In complex anatomies, CT reconstruction can predict optimal projections during transcatheter interventions.

DEVICE SELECTION

A primary goal of transcatheter treatment is to rapidly and effectively decompress the right ventricle by reducing

Abbreviations

CAVT	computer-assisted vacuum thrombectomy	**CT**	computed tomography	**PAP**	pulmonary artery pressure
CDMT	catheter-directed mechanical thrombectomy	**ECMO**	extracorporeal membrane oxygenation	**PE**	pulmonary embolism
		LV	left ventricle	**RV**	right ventricle
CDT	catheter-directed thrombolysis	**MPA**	main pulmonary artery	**TAPSE**	tricuspid annular plane systolic excursion

thrombus burden, decreasing RV afterload and increasing left ventricular (LV) preload, thereby improving systemic perfusion[15]. The decision on treatment selection between CDT or CDMT often relies on the clinical presentation, the location and burden of the thrombus, the predicted risk of bleeding, institutional availability and operator expertise **(Central illustration)**[2]. The proposed approach is based on currently available data and institutional experience. In haemodynamically unstable PE patients in whom systemic thrombolysis is contraindicated or has failed, CDMT should be preferred because of its faster improvement of haemodynamic status compared to CDT, where thrombolytic infusion occurs over 6-24 hours[16-18]. In addition, in centres with appropriate expertise, extracorporeal membrane oxygenation (ECMO) support could be anticipated in order to rapidly stabilise a patient before mechanical reperfusion. In haemodynamically stable patients, treatment selection could be individualised based on the anatomical distribution of the thrombus and bleeding risk. In case of large volume clots located proximal to the origin of the segmental pulmonary arteries or clots in transit (located in the right atrium, RV, or PFO), large-bore CDMT may be preferred. Whereas, in case of a smaller volume, uniformly dispersed clot, or a clot that extends distal to the origin of the segmental pulmonary arteries, CDT may be preferred. In case of high bleeding risk patients and relative or absolute contraindications to thrombolysis **(Table 1)**, CDMT should be preferred over CDT. Finally, the choice of a specific CDMT system should be based on operator experience and institutional availability, considering the trade-off between larger-bore devices (e.g., 20-24 Fr), which offer higher aspiration performance but increased stiffness, and medium-bore devices (e.g., 12-16 Fr), which provide better trackability and access to more distal segments at the expense of potentially lower aspiration force.

Catheter-directed therapy selection based on clinical presentation, bleeding risk and thrombus location.

Treatment strategies based on clinical status with or without absolute contraindications to thrombolysis, haemodynamic stability and thrombus location. The red dashed line represents the option of having ECMO in addition to catheter-directed mechanical thrombectomy. The grey dashed line represents the option of applying concomitant systemic thrombolysis to catheter-directed mechanical thrombectomy. The blue box represents the area of possible application of CDT as an alternative to CDMT. CDMT: catheter-directed mechanical thrombectomy; CDT: catheter-directed thrombolysis; ECMO: extracorporeal membrane oxygenation; int: intermediate

Table 1. Risk features for high bleeding risk, and relative and absolute contraindications to thrombolysis.

High bleeding risk features during antithrombotic therapy	Relative contraindications to thrombolysis	Absolute contraindications to thrombolysis
Advanced age (>75 years)	Recent transient ischaemic attack (<6 months)	Prior haemorrhagic stroke
Advanced renal disease	Ongoing oral anticoagulation	Recent ischaemic stroke (<6 months)
Active cancer	Pregnancy or first postpartum week	Central nervous system neoplasm
Severe anaemia (<11 g/dl)	Non-compressible puncture sites	Recent major trauma, surgery, or head injury (<3 weeks)
Recent spontaneous bleeding (<6 months)	Traumatic resuscitation	Current active bleeding
Bleeding diathesis	Use of ECMO	
	Advanced liver disease	
	Infective endocarditis	
	Active peptic ulcer	
	Refractory hypertension (systolic BP >180 mmHg)	

BP: blood pressure; ECMO: extracorporeal membrane oxygenation

Recently, the PEERLESS trial provided the first direct comparison between large-bore CDMT and CDT in patients with intermediate-risk PE. Large-bore CDMT was performed using the FlowTriever system (Inari Medical), while CDT was conducted according to local standard practices, with 59.8% utilising ultrasound-accelerated CDT[19]. The composite primary endpoint occurred significantly less frequently with large-bore CDMT. This was driven by a lower rate of clinical deterioration, reduced need for escalation to bailout procedures, and decreased postprocedural intensive care unit (ICU) utilisation. There were no significant differences between the two groups in all-cause mortality, intracranial haemorrhage, or major bleeding events. Comparisons of CDMT and CDT with the standard care of systemic anticoagulation are currently under investigation in dedicated randomised controlled trials (ClinicalTrials.gov: NCT06055920, NCT04790370, NCT05591118, NCT05684796).

Catheter-directed thrombolysis

CDT allows the local infusion of a low-dose thrombolytic agent into the pulmonary artery or directly into the thrombus. Currently, two main techniques are available: conventional local thrombolysis, which can be performed via a common pigtail catheter or via dedicated catheters (Uni-Fuse [AngioDynamics]; Cragg-McNamara [Medtronic]; Pulse*Spray infusion system [AngioDynamics]; BASHIR [Thrombolex]), and ultrasound-accelerated catheter-directed thrombolysis, in which a dedicated catheter emits 2 MHz ultrasound waves during thrombolytic infusion to allow the disaggregation of fibrin fibres and drug penetration into the thrombus. The EKOS system (Boston Scientific) is currently the most commonly used dedicated CDT system. According to a European survey, it is implemented in up to 20.2% of catheter-directed cases[20] and has been investigated in multiple randomised trials[21,22]. Nevertheless, there is still a lack of definitive evidence to support the superiority of dedicated CDT devices over standard catheters for local thrombolysis, which should be considered based on their lower cost and ease of use[22].

PROCEDURAL STEPS, TIPS AND TRICKS

The EKOS system is composed of an infusion catheter with an ultrasonic core and a control unit with connector interface cables **(Figure 2)**. The device is available in various lengths – 6, 12, 18, 24, 30, 40, and 50 cm – allowing selection based on the measured length of the thrombus. For pulmonary clots, shorter lengths, such as 12 and 18 cm, are generally preferred. First, central venous access is established, typically via the femoral vein, or alternatively through the jugular or basilic vein, with echo guidance recommended to detect the thrombus and reduce complications. Two packages are used: one for the infusion catheter and one for the ultrasonic core. System priming is obtained by flushing the catheter drug lumen with heparin and the coolant lumen with heparinised saline. Based on thrombus distribution, single-sided or two-sided therapy could be selected. Once the target pulmonary vessel is reached with standard catheters, a 0.035" exchange length guidewire is used to place the distal marker of the infusion catheter 1 cm beyond the target clot **(Figure 2B)**. Catheter placement in the basal segments should be preferred to increase system stability and reduce complications. Once the infusion catheter is in place, the 0.035" wire is removed and the ultrasonic core is advanced into the guidewire lumen, paying attention not to kink or bend it **(Figure 2C, Figure 3)**. When the ultrasonic core is locked into the manifold, the infusion of heparinised saline through the coolant port is started at 35 ml/h, and the infusion of the lytic through the drug port is started at 5-35 ml/h at the desired dosage (e.g., 4-10 mg recombinant tissue plasminogen activator per lung for 2-12 hours depending on the chosen protocol) **(Table 2, Figure 2D)**. The interface cable is connected to the control unit and then the device cables to the single interface unit **(Figure 2E)**. When the device is properly connected, the instructions on the screen should be followed to begin ultrasound emission **(Figure 2F)**. In summary:

- Use ultrasound guidance for safe venous access and detecting peripheral vein thrombi.
- Choose an infusion catheter length that matches the thrombus size to ensure effective thrombolysis.
- Decide on single or bilateral catheter placement based on thrombus distribution. Position the infusion catheter's distal marker 1 cm beyond the target clot, preferentially in basal segments to enhance stability and reduce complications.

Catheter-directed mechanical thrombectomy

Contemporary CDMT involves aspirating thrombi from the pulmonary artery using percutaneous catheters via femoral
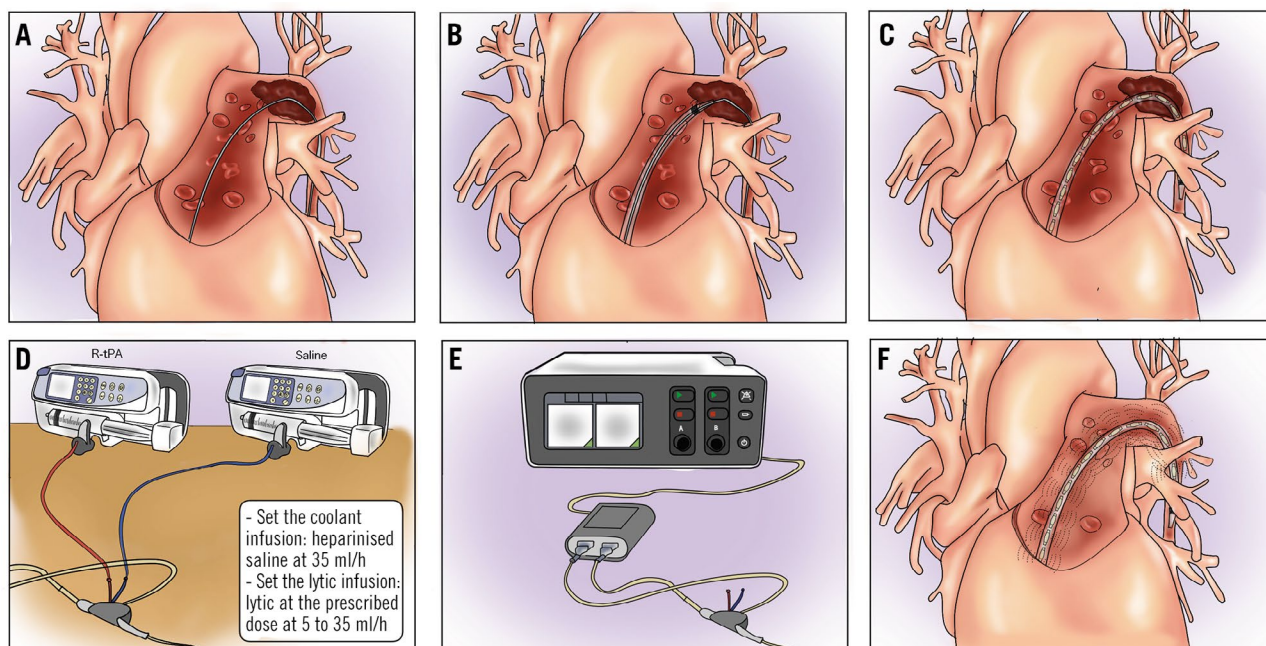
Figure 2. *Ultrasound-accelerated catheter-directed thrombolysis with the EKOS system. A) Guidewire positioning (basal segments are preferred). Positioning of the EKOS infusion catheter over the wire and guidewire removal (B). Positioning of the ultrasound probe in the infusion catheter (C). Setting the infusion of the thrombolytic agent and coolant solution; 2 infusion systems are needed for each EKOS catheter (D). Once the infusion of the coolant and thrombolytic agent has been started, ultrasound emission may be initiated (E). Leave the infusion catheter in place during treatment for the prescribed duration (F). Check the result at bedside by temporarily interrupting the emission of ultrasound from the device console. EKOS system by Boston Scientific.*
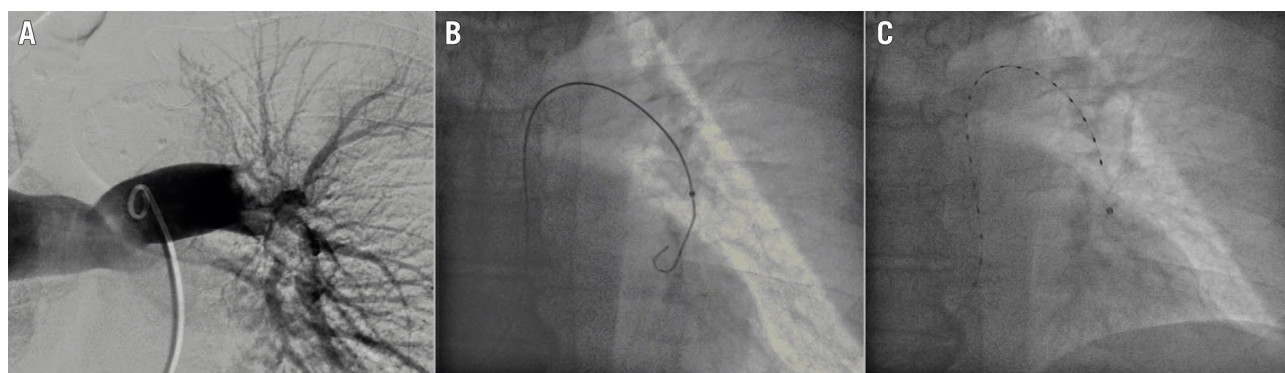
Figure 3. *Ultrasound-accelerated catheter-directed thrombolysis with the EKOS system: clinical case. Pulmonary embolism with nearly complete occlusion of the left pulmonary artery (A). Positioning of the guidewire in the basal segment of the left pulmonary artery (B). EKOS infusion and ultrasonic catheter in place (C). EKOS system by Boston Scientific.*

or jugular venous access. There are currently two devices that are approved for percutaneous treatment of PE and do not require the support of a perfusionist: the FlowTriever system and the Lightning Flash thrombectomy system (Penumbra)[23,24]. The additional benefit of these systems is that they can be used in patients who have an absolute or relative contraindication to thrombolytics and, off-label, can even be used without systemic anticoagulation. The FlowTriever is a large-bore catheter system comprising a 24 Fr catheter connected to a high-pressure syringe to create a vacuum (with other accessories such as a longer 16 Fr catheter, a curved 20 Fr catheter, and a set of nitinol disks to fragment the thrombus). This system is effective for rapid clot debulking but requires a large vascular access and may be more challenging if needed for reaching a distal clot **(Figure 4, Figure 5)**. Contrarily, the Lightning system uses a 12 Fr catheter connected to an automatic negative pressure pump that allows selective aspiration when

Table 2. Dose regimens of tissue plasminogen activator tested in clinical trials of catheter-directed thrombolysis.

| Dose regimens of tPA	
Dose regimen of tPA implemented in the OPTALYSE PE trial[35]	
Arm 1	4 mg per lung over 2 h
Arm 2	4 mg per lung over 4 h
Arm 3	6 mg per lung over 6 h
Arm 4	12 mg per lung over 6 h
Dose regimen of tPA implemented in the SEATTLE II trial[36]	
Unilateral PE (1 catheter)	1 mg/h over 24 h
Bilateral PE (2 catheters)	1 mg/h per lung over 12 h
Dose regimen of tPA implemented in the HI-PEITHO trial[8]	
Unilateral PE (1 catheter)	9 mg, 2 mg bolus followed by 1 mg/h infusion over 7 h
Bilateral PE (2 catheters)	18 mg, 2 mg bolus followed by 1 mg/h infusion over 7 h per lung

PE: pulmonary embolism; tPA: tissue plasminogen activator

engagement with the clot is sensed and allows a separator to be used when the clot obstructs the catheter lumen **(Figure 6, Figure 7)**. The reduced profile allows for a smaller access site and can address a clot that is located more distally in the pulmonary tree but also limits its aspiration capability with larger clots[25]. Lately, a new 16 Fr system with computer-assisted vacuum thrombectomy (CAVT; Penumbra) technology has been introduced to increase aspiration power and reduce blood loss. The 16 Fr catheter, available with a single or a double curve, allows trackable and atraumatic advancement even without a guidewire in place.

PROCEDURAL STEPS, TIPS AND TRICKS

After obtaining venous access, a balloon catheter (or pigtail, alternatively) should be used to advance through the tricuspid valve into the pulmonary artery, preventing entanglement or damage to the subvalvular apparatus by larger catheters. Right heart catheterisation and pulmonary angiography should be performed as previously mentioned. Vessel selection for interventional treatment should prioritise segments with total occlusion without distal visualisation. In cases of subtotal occlusion, a lower success rate and the risk of possible distal embolisation with clinical destabilisation should be considered. A multipurpose catheter with a 0.035" wire is commonly used to cross the thrombus and gain distal position. Hydrophilic guidewires are effective in challenging situations, but an increased risk of distal perforation should be considered. A torqueable, soft-tip wire (e.g., Wholey wire [Medtronic]) may also be useful in challenging cases. Proper distal positioning of the catheter is essential for advancing a high support guidewire with a short, floppy tip (1 cm). This positioning ensures stability when introducing large-bore catheters and minimises the risk of distal perforation. The lower branches of the right or left pulmonary artery (e.g., segments A8-A10) **(Supplementary Figure 1)** should be preferred, and it is
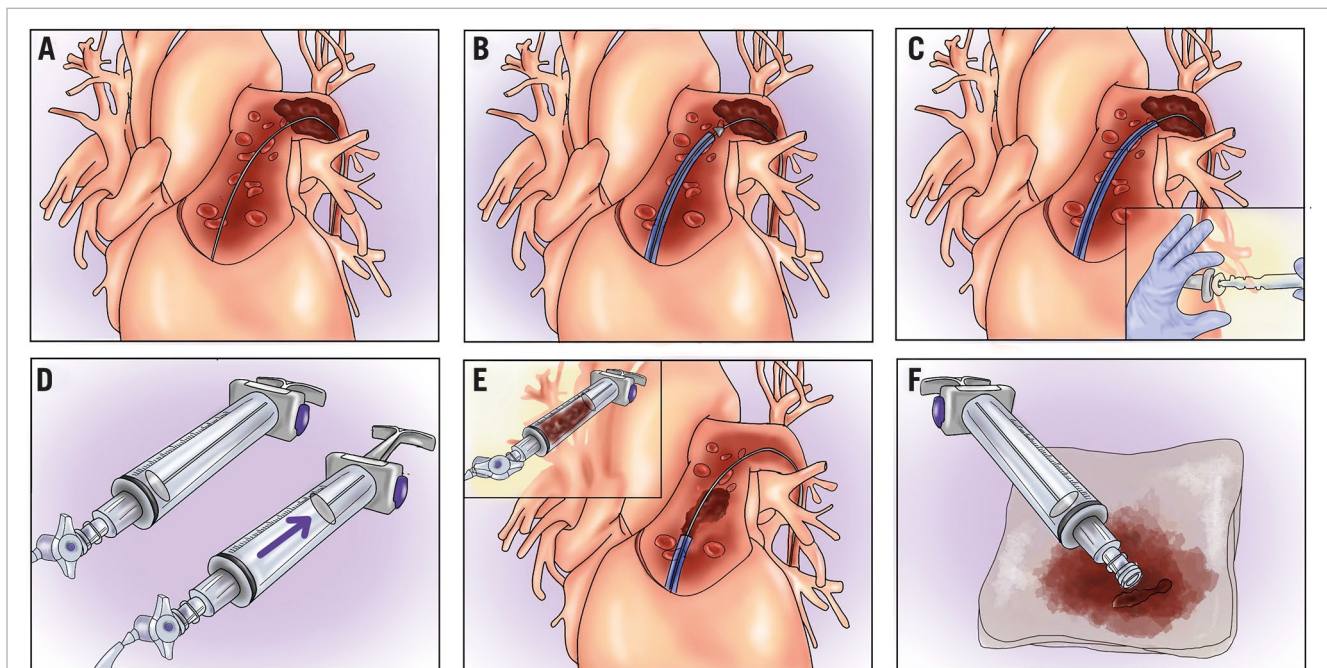
Figure 4. *Catheter-directed mechanical thrombectomy with the FlowTriever system. A) Guidewire positioning (generally basal segments are preferred with a high support wire). Advance the aspiration catheter with the inner dilator to avoid vascular damage and approach the thrombus (B). Remove the inner dilator, leaving the guidewire in place to avoid vascular damage (C). Create a vacuum with the syringe aspirator (D) and open the pressure valve to aspirate the thrombus; aspirating in proximity to the thrombus with the "whoosh" technique is advised (E). Remove thrombi or use the dedicated FlowSaver filter (Inari Medical) for blood return (F). FlowTriever system by Inari Medical.*
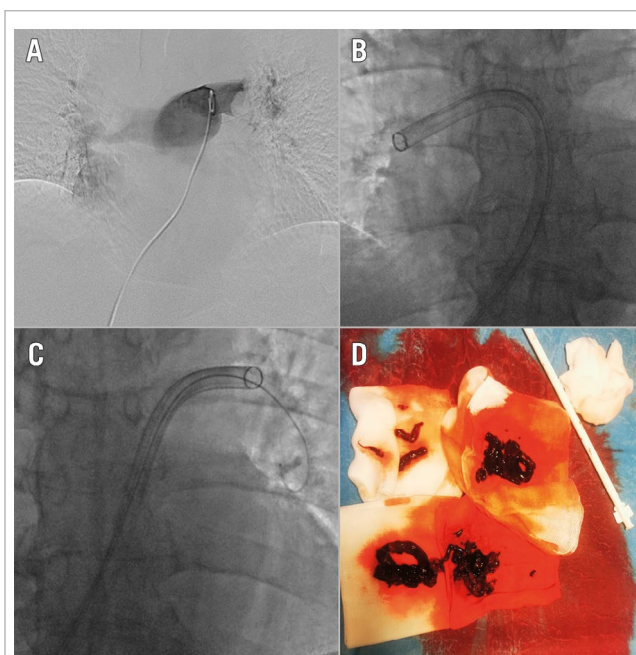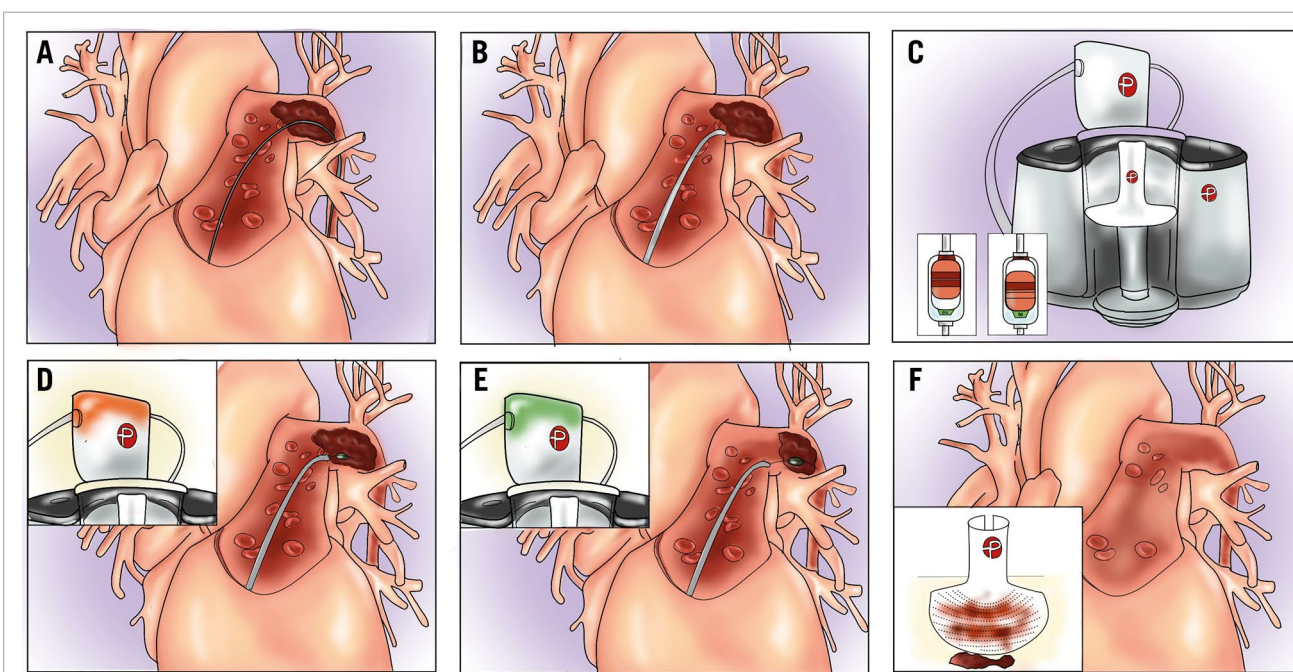
Figure 5. *Catheter-directed mechanical thrombectomy with the FlowTriever system: clinical case. Pulmonary angiography with evidence of bilateral pulmonary embolism (A). FlowTriever system (Inari Medical) in the right and left pulmonary arteries (B-C). Large clot burden removed after thrombus aspiration (D).*

important to confirm that the target vessel is large enough to accommodate the procedure. Lingula segments should be avoided because of the increased risk of distal perforation. After proper wire positioning, the CDMT system can be introduced. The FlowTriever navigates directly from a short femoral sheath, while the Lightning system usually is used in combination with a long sheath (e.g., 60 cm or 80 cm) that reaches the main pulmonary artery. During advancement, special care should be taken in patients with previous left bundle branch block, as instrumentation with large-bore catheters of the right ventricular outflow tract might induce complete heart block.

CDMT WITH INARI MEDICAL'S FLOWTRIEVER

If the FlowTriever catheter is selected, it is safely advanced using dedicated catheter dilators that cover the sharp edge of the catheter, avoiding vascular wall damage (razor effect) **(Figure 4B)**. Navigation is usually simple; however, in case of challenging catheter tracking, an "inverted" mother-and-child technique, advancing the larger catheter through a narrower and longer one could be useful **(Figure 8)**. CDMT may be initiated in the right pulmonary artery as it provides greater stability, simpler navigability, and a higher aspiration-to-time ratio. Once the target thrombus is reached, aspiration can be initiated, maintaining the guidewire in place, which reduces the risk of potential vascular damage. Aspiration attempts should be initiated from proximal to distal, with the catheter tip proximal to the thrombus to avoid catheter obstruction

Figure 6. *Catheter-directed mechanical thrombectomy with the Lightning Flash system. A) Guidewire positioning (generally basal segments with high support wire are preferred). Advance the aspiration catheter over the wire and approach the thrombus (B). Activate the aspiration switch (C). Discontinuous aspiration will start removing thrombotic material (flashing green light). If the thrombus totally obstructs the catheter lumen, a flashing yellow light will appear (D). Reposition the catheter or use the separator to re-establish aspiration. A flashing green light will confirm successful aspiration (E). Check the amount of thrombus and blood aspirated in the console filter (F). Lightning Flash system by Penumbra.*
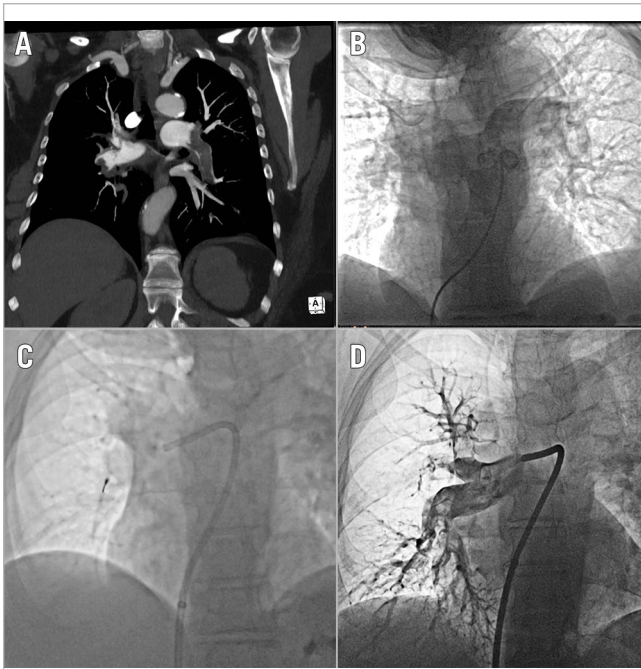
Figure 7. *Catheter-directed mechanical thrombectomy with the Lightning Flash system: clinical case. CT angiogram showing bilateral pulmonary embolism (A). Baseline pulmonary artery angiogram (B). Selective cannulation of the right pulmonary artery with the Lightning Flash catheter and separator advanced in the right interlobar artery (C). The postprocedural selective angiogram of the right pulmonary artery shows revascularisation of the interlobar artery with moderate residual thrombus. Lightning Flash system by Penumbra. CT: computed tomography*

(Figure 4C-Figure 4E). If free-flowing blood with no clot is aspirated, the catheter should be repositioned closer to the thrombus. If the aspirated material is a mix of blood and clot, additional aspirations can be performed at the discretion of the operator. Considering the significant amount of blood loss with these manoeuvres, careful evaluation of the total amount of blood removed and the baseline haemoglobin values should be considered during the procedure to avoid severe anaemia. To limit this issue, blood reinfusion systems (e.g., FlowSaver [Inari Medical]) have recently become available. In case the aspirated thrombus is occluding the catheter tip during aspiration, it is recommended to perform a second additional aspiration ("double whoosh") to retrieve the clot. If this is not effective and the catheter remains obstructed during aspiration, removing the catheter over the wire while maintaining suction ("lollipop" technique) should be considered. This manoeuvre should be performed with care to avoid embolisation and should not be performed in case of a PFO due to a possible risk of paradoxical embolisation[26]. After performing thrombectomy in the first artery or branch, the catheter may be safely redirected to different vessels using a parallel wire technique **(Figure 8)**. The previous steps are repeated until the procedure is concluded. In case of more distal thrombus retrieval from smaller pulmonary branches,

distal aspiration with the 16 Fr catheter can be considered using a child-in-mother technique **(Figure 8)**. Thrombi that are adherent to the vessel wall can be difficult to reach and remove, particularly in the inner curve at the level of the interlobar artery, as the guidewire tends to follow the outer curve, preventing the catheter from making contact with the thrombus. In such cases, the Triever20 Curve catheter (Inari Medical), a 20 Fr steerable catheter, is advanced within the 24 Fr system with the distal tip curving up to 225° to approach wall-adherent thrombi. This is particularly useful in the left pulmonary artery interlobar segment, where the curved catheter has a higher chance of being coaxial with the distal vessel and making contact with the thrombus. In cases of a subacute/chronic thrombus that is highly adherent to the vessel wall, mechanical thrombectomy using nitinol disks can be performed. The disks, which are sized according to the target vessel diameter, are advanced inside the thrombus and left in place for 2 minutes to allow slight thrombus compression, then removed. Following this procedure, it is advisable to attempt thrombus aspiration again, as its effectiveness tends to be higher after disk use. In summary:

- Cross the tricuspid valve with a balloon-tipped catheter to avoid chordae entanglement.
- Use a catheter dilator when advancing it to avoid vessel wall injury.
- Start aspiration proximal to the thrombus to prevent catheter blockage.

CDMT WITH PENUMBRA LIGHTNING

If the Penumbra system is used, the same technique could be used to cross the tricuspid valve and track the device in proximity to the clot **(Figure 6, Figure 7)**. A 16 Fr long sheath could be useful to improve device tracking with the 12 Fr catheter, while such a sheath is not necessary with the new 16 Fr catheter. Once the catheter has been advanced and the clot has been reached, aspiration can be initiated by turning on the flow switch and advancing the catheter through the thrombus **(Figure 6B, Figure 6C)**. The 12 Fr Lightning system provides intermittent intelligent aspiration to reduce blood loss, accompanied by a light and sound indication of the aspiration status: a flashing green light indicates intermittent aspiration of the clot from the catheter. In case of catheter obstruction, a flashing yellow light will indicate the need to redirect the catheter or use the separator to break the clot and continue aspiration **(Figure 6D, Figure 6E)**. The amount of clot/blood aspirated can be checked through the console. The new CAVT technology allows for more precise aspiration, signalling with a solid green light when the catheter has not reached the thrombus, and a solid yellow light when the thrombus has been reached, at this stage activating faster suction (which is also associated with a higher frequency sound from the aspiration device) that forces clot extraction and automatically reduces the aspiration force once the resistance reduces. In case the catheter is totally obstructed by the thrombus, as prevously mentioned, a flashing yellow light will appear, indicating the need to change catheter position or proceed to catheter removal (lollipop technique). In summary:

- Cross the tricuspid valve with a balloon-tipped catheter to avoid chordae entanglement.

Figure 8. *Techniques of catheter-directed mechanical thrombectomy in challenging anatomies. Inverted mother-and-child technique to facilitate FlowTriever 24 Fr catheter (Inari Medical) advancement over a FlowTriever 16 Fr distal catheter (A). Parallel wire technique to switch selective cannulation of a FlowTriever 24 Fr catheter from the right to the left pulmonary artery in a challenging anatomy (B). The extra support wire is maintained in the first branch to stabilise the catheter and prevent withdrawal into the right ventricle; the catheter is retrieved enough to be able to insert and advance a multipurpose long catheter (parallel to the first wire) into the next branch. After positioning the long catheter distally in that branch, a high support wire is advanced through it, the first wire can be retrieved, and the catheter is advanced over the new high support wire towards the second branch.*

- Pay close attention to the system's visual and auditory cues to optimise aspiration and minimise blood loss.
- In case of obstruction with the 12 Fr system, use the separator to re-establish aspiration.

TERMINATION OF THE CDMT PROCEDURE

After CDMT, follow-up angiograms can be performed either directly via the thrombectomy catheter or through a pigtail catheter, ensuring that the catheters are free of thrombi (**Figure 5**, **Figure 7**). There is no consensus on the definition of reperfusion success with CDMT. As a general rule, removal of all the thrombotic material is not necessary, as clinical improvement is generally obtained even with modest clot extraction. Procedural elements that inform the conclusion of a CDMT are summarised in **Table 3**[27]. After catheter removal, haemostasis is achieved with different techniques according to operator preferences – figure-of-eight stitch, purse-string suture, Perclose device (Abbott), or manual compression.

Control of postprocedural treatment efficacy and monitoring

Postprocedural treatment efficacy should be evaluated based on haemodynamic, imaging and laboratory parameters, with signs of clinical improvement generally observed immediately after CDMT, and 2-6 hours after CDT **(Figure 1)**. From a clinical standpoint, systemic blood pressure and heart rate are simple clinical markers of early improvement. A European consensus paper suggests the use of the National Early Warning Score (NEWS) as a monitoring tool to detect clinical deterioration[28]. Although there is a lack of evidence supporting this recommendation, the same tool could also be used to monitor clinical improvement. Echocardiography is useful to evaluate treatment efficacy at bedside, yet in case of CDT with EKOS, ultrasound emission should be interrupted to avoid artefacts. Non-invasive imaging markers of treatment response are a change in RV/LV diameter ratio from baseline, pulmonary artery systolic pressures, change in right atrial dimension, tricuspid annular plane systolic excursion (TAPSE) and other indices of RV contractility. In a meta-analysis evaluating the clinical and haemodynamic impact of ultrasound-assisted CDT in patients with intermediate- or high-risk pulmonary embolism, after treatment the RV/LV ratio was reduced by 35% (95% confidence interval [CI]: 30-40%), pulmonary artery systolic pressure by 16.69 mmHg (95% CI: 13.65-19.73 mmHg), while TAPSE improved by 3.68 mm (95% CI: 2.43-4.93 mm) and cardiac index by 0.68 l/m^2 (95% CI: 0.49-0.87 l/m^2)[29]. Similar results have been observed with echocardiography 48 hours after CDMT: in the FLASH registry, the echocardiographic RV/LV ratio at 48 hours decreased from 1.23±0.36 to 0.98±0.31, while RV systolic pressure was reduced by 13.4 mmHg[30]; in the interim analysis of the STRIKE-PE registry, the RV/LV ratio at 48 hours decreased from 1.39±0.35 to 1.01±0.21[31]. Laboratory testing could also be useful to guide postprocedural treatment strategy. Reduction of lactates is a key element to determine circulatory improvement. Serial monitoring of troponin[32] or

Table 3. Procedural elements for informing treatment cessation during catheter-directed mechanical thrombectomy.

Procedural elements
1. Improvement of haemodynamic status, achieving clinical stability
2. Improvement in mean pulmonary artery pressure (e.g., ≤20 mmHg or at least a 7 mmHg drop)
3. No more thrombi can be reasonably removed (e.g., all proximal thrombi have been removed; only a chronic or highly organised thrombus remains, or anatomical impediments to reaching the thrombus)
4. Unfavourable blood loss trade-off (e.g., blood loss over 400 cc)

N-terminal pro-brain natriuretic peptide[33] has been evaluated in small series. It is important that haemoglobin values are evaluated after CDMT, as significant blood loss can occur. After CDT, on the other hand, fibrinogen levels can be monitored (e.g., every 2 hours) during thrombolytic infusion to limit the risk of bleeding complications. Postprocedural close monitoring of the patient in an intermediate or critical care unit is recommended after either CDT or CDMT.

Complications

While catheter-directed therapies have generally demonstrated low complication rates in expert centres[34], the potential risk for life-threatening complications should be acknowledged and anticipated **(Table 4)**. In recent international registries, major bleeding has been reported in up to 5% and 9% of CDT- and CDMT-treated patients, respectively, while intracranial haemorrhage has remained rarely observed, in less than 1% of cases. In-hospital cardiac arrest has been observed in 4% and 8% of patients, while in-hospital mortality has been observed in 4% and 10% of patients with CDT and CDMT, respectively[12].

Specific complications relative to transcatheter interventions are presented in **Table 4** and extensively discussed in **Supplementary Appendix 1**.

Future technologies

Several devices will expand the armamentarium for PE treatment. These are presented in **Table 5** and extensively discussed in **Supplementary Appendix 2**.

Table 4. Potential complications of catheter-directed therapies for pulmonary embolism.

Complication	Frequency	Cause	Solution
Sudden haemodynamic collapse	Uncommon	Fragmentation of the thrombus during mechanical thrombectomy increases pulmonary resistance	Increase inotropes VA-ECMO Intraprocedural thrombolysis
		Increased right ventricular strain due to excessive catheter manipulation	Catheter removal Intraprocedural thrombolysis VA-ECMO
		Incorrect tricuspid valve crossing determining acute tricuspid insufficiency or rupture	Catheter removal Cardiac surgery
		Free wall perforation and cardiac tamponade	Pericardiocentesis Cardiac surgery
Haemoptysis	Uncommon	Guidewire tip perforation	Ventilatory support, selective intubation if needed Reverse heparin Balloon inflation Selective coiling
		Large branch perforation	Ventilatory support, selective intubation if needed Reverse heparin Balloon inflation Cardiac surgery
		Reperfusion injury	Ventilatory support, selective intubation if needed
Large branch dissection	Rare	Excessive catheter manipulation	Generally self-limiting CTA during FU Balloon inflation
Paradoxical embolism	Rare	Systemic embolism through a patent foramen ovale or other congenital defects	Specific management according to the embolism site
Non-pulmonary bleedings	Uncommon	Excessive antithrombotic treatment or side effect of thrombolysis	Stop thrombolysis Reverse heparin Specific management according to the bleeding site

CTA: computed tomography angiography; FU: follow-up; VA-ECMO: venoarterial extracorporeal membrane oxygenation

Table 5. Novel devices and future technologies for catheter-directed treatment of pulmonary embolism.

Device	Description	FDA approval status	CE approval status	Study/trial	NCT number	Population number (n)
AlphaVac F18[a]	Thrombectomy device for mechanical thrombus aspiration	FDA-approved	CE-approved	APEX-AV	NCT05318092	122
Hēlo PE[b]	Thrombectomy device combining mechanical clot disruption with aspiration	Currently not approved	Currently not approved	ENGULF	NCT05597891	25
WOLF[c]	Thrombectomy device using finger-like prongs for controlled emboli removal	Approved for peripheral arteries Currently not approved for PE	Currently not approved	N/A	N/A	N/A
JETi[d]	Thrombectomy device with a high-pressure jet of saline to break up thrombus to facilitate aspiration	Approved for peripheral arteries Currently not approved for PE	Currently not approved	N/A	N/A	N/A
Laguna[e]	Thrombectomy device combining mechanical clot disruption with aspiration	Approved for peripheral arteries Currently not approved for PE	Currently not approved	TRUST	NCT06041594	107 estimated patients
Cleaner Pro[f]	Thrombectomy device combining thrombectomy and infusion of thrombolytics	Approved for peripheral arteries Currently not approved for PE	Currently not approved	CLEAN-PE	NCT06189313	125 estimated patients
Katana[g]	Thrombectomy device combining rheolytic-powered aspiration and directional features	Currently not approved	Currently not approved	QUADRA-PE	NCT06672510	118 estimated patients
Magneto eTrieve[h]	Thrombectomy device combining large-bore aspiration with electromechanical thrombus extraction	Currently not approved	Currently not approved	Evaluation of the Safety and Performance of Magneto PE Kit	NCT04949048	10

[a]By AngioDynamics; [b]by Endovascular Engineering; [c]by Boston Scientific; [d]by Abbott; [e]by Innova Vascular; [f]by Argon Medical Devices; [g]by Akura Medical; [h]by Magneto Thrombectomy Solutions. CE: European Conformity; FDA: U.S. Food and Drug Administration; N/A: not applicable; PE: pulmonary embolism

Conclusions

While anticoagulation remains the foundation of PE treatment and the main treatment option in most PE patients, the advent of catheter-directed therapies offers promising alternatives for selected patients. A comprehensive, patient-centred approach, integrating advanced catheter technologies with meticulous procedural planning, remains paramount in the evolving landscape of PE treatment. Future randomised controlled trials, together with new devices and techniques, hold the potential to significantly refine our understanding and application of these interventions, aiming to improve patient outcomes and minimise risks.

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Conflict of interest statement

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Supplementary data

Supplementary Appendix 1. Complications of catheter-based interventions.
Supplementary Appendix 2. Future technologies.
Supplementary Table 1. Differential CT features of acute and chronic pulmonary embolisms.
Supplementary Figure 1. Pulmonary vascular anatomy.

The supplementary data are published online at: https://eurointervention.pcronline.com/ doi/10.4244/EIJ-D-24-00535

Supplementary data

Supplementary Appendix 1. Complications of catheter-based interventions.

Hemodynamic collapse: Hemodynamic collapse during CDT and CDMT represents a critical and life-threatening complication that demands immediate and decisive management. Hemodynamic collapse in this context refers to the sudden deterioration of cardiovascular function, manifesting as severe hypotension, bradycardia, or cardiac arrest.[37] This complication can arise due to dislodgement of thromboembolic material, leading to further obstruction of the pulmonary arteries and an increase in RV afterload, or due to excessive catheter manipulation that can precipitate arrhythmias or cardiac tamponade.[38] A correct patient clinical evaluation before starting the procedure is crucial to establish the hemodynamic status. In selected cases, a "protected procedure" with veno-arterial extracorporeal membrane oxygenation (VA-ECMO) is indicated for patients in advanced shock stages.[39] Management strategies of this complication encompass advanced cardiovascular life support (ACLS) protocols, including rapid fluid resuscitation, vasopressor support, and, if necessary, cardiopulmonary resuscitation (CPR). Simultaneously, the procedural team should swiftly address the underlying cause. Intraprocedural thrombolysis or emergent surgical embolectomy may be performed in selected cases.[28] Additionally, echocardiography can be instrumental in diagnosing potential complications such as pericardial effusions, which may require pericardiocentesis.[40]

Haemoptysis: Pulmonary artery injury, resulting from aggressive catheter manipulation, can lead to hemoptysis or pulmonary hemorrhage. Large branch perforations are particularly dangerous, often requiring immediate surgical intervention.[41] Distal perforations are not uncommon and are generally caused by the guidewire tip, especially in patients previously treated with thrombolysis. Hemoptysis during these procedures necessitates immediate evaluation to determine the source and extent of the bleeding. Distal tip perforation often resolve spontaneously, however, if hemoptysis persists, prolonged balloon inflation or distal embolization with endovascular coils may be required.[42] Reperfusion injury is another significant concern due to sudden restoration of blood flow to the affected lung areas causing inflammation and tissue damage, leading to respiratory distress, respiratory failure, or hemoptysis. This condition is often self-limiting, but in some occasions may require anticoagulation reversal and stabilization with orotracheal intubation.

Other Complications: Vascular dissections may rarely occur secondary to aggressive catheter manipulation. These generally involve segmental segments and are mostly self limiting.[43] Proximal segments dissection however may be life-threatening and require reversal of anticoagulation, and surgical or percutaneous intervention to reestablish antegrade flow.[44] Systemic thromboembolism, although rare, is possible if dislodged thrombus migrates through a patent foramen ovale (PFO), especially during a "lollipop technique". Due to the increasing right heart pressure a paradoxical shunt from right to left heart may increase the risk of paradoxical embolism in these situations.[26] The presence of PFO must be carefully evaluated especially in case of thrombi in transit through the tricuspid valve or right atrium.[45]

Supplementary Appendix 2. Future technologies.

Several new devices are expected to enhance the armamentarium for PE transcatheter treatment in the near future. The AlphaVac F18 is a mechanical thrombectomy device that utilizes vacuum technology to aspirate and remove clots, minimizing blood loss and eliminating the need for thrombolytic therapy. The system includes an ergonomic handle, an 18F cannula with an 85-degree angle, and a 33F larger self-expandable head to facilitate clot approach. The AlphaVac F18 system was recently evaluated in the APEX-AV study and received FDA 510(k) clearance for the treatment of PE in April 2024.[46] The Helo PE is a dual-action thrombectomy device that combines mechanical clot disruption with aspiration. Its design allows for both mechanical fragmentation of the clot and simultaneous suction. Preliminary results in the ENGULF trial have shown promise.[47] However, as of now, the Helo PE is still under evaluation and has not yet received FDA approval. The WOLF device by Devoro Medical, now part of Boston Scientific, presents an innovative approach to thrombectomy. It is designed to mechanically capture and remove clots from the pulmonary arteries, providing more controlled and precise removal of emboli with finger-like prongs that retrieve and remove thrombi. Although the WOLF device has been FDA-approved since 2019, it is currently indicated only for the removal of thrombus from peripheral arteries.

Supplementary Table 1. Differential CT features of acute and chronic pulmonary embolisms.

Feature	Acute Pulmonary Embolism	Chronic Pulmonary Embolism
Thrombus Localization	Central localization within the lumen	Eccentric broad-based filling defects adherent to vessel wall
Vessel Appearance	Peripheral opacification of the vessel ('polo mint sign') or complete obstruction with enlargement of vessel distal to the obstruction	Complete obstruction with vessel diameter distal to clot contracted
Thrombus Characteristics	Homogeneous density	Calcification of clots, presence of linear filling defects (webs and bands)
Indirect Signs	Acute right ventricular overload (IVC reflux, increased RV/LV ratio)	Pulmonary hypertension signs (right ventricle hypertrophy, pulmonary artery dilation >29mm)
Parenchymal Signs	Hypoperfusion to lung triangular-shaped infarction	Pulmonary parenchymal mosaic perfusion
Vascular Changes	No specific vascular changes	Chronic vascular changes (post-stenotic dilation, collateral bronchial supply)
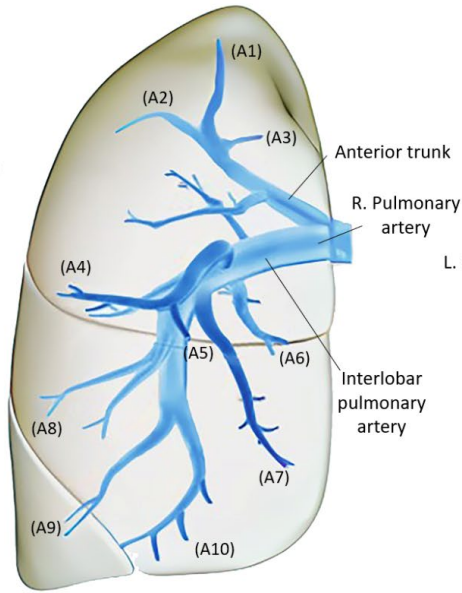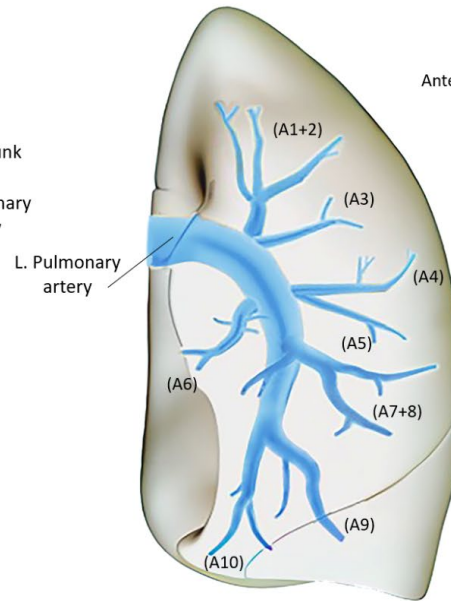
Supplementary Figure 1. Pulmonary vascular anatomy.

In the typical vascular anatomy, after branching from the main pulmonary artery (MPA), the right pulmonary artery (RPA) bifurcates into the truncus anterior and the interlobar artery, while the left pulmonary artery (LPA) divides into two main basal branches. Each of these further divide, resulting in a total of 10 segmental vessels for each lung.