Technical Considerations for Percutaneous Pulmonary Artery Cannulation for Mechanical Circulatory Support

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Abbreviations:

Central Message:
Percutaneous pulmonary artery cannulas, used either as inflow for left ventricular venting or as outflow for right ventricular mechanical circulatory support, are easily and rapidly deployable.

Central Picture:

Central Picture Legend:
Wire and cannula positioning for right atrium to pulmonary artery cannulation.

Perspective Statement:
The deployment of percutaneous right atrium to pulmonary artery cannulas are easily and rapidly deployable. Due to this feature, they can be used prophylactically in patients with high-risk features for acute right ventricular failure. They provide an excellent flow profile and the various number of versatile flow configurations may position it to be preferred over surgical cannulation. These cannulas can also be safely deployed in the intensive care unit and bedside under fluoroscopy and transesophageal echocardiography guidance.
Structured Abstract

Objectives

Percutaneous cannulas pulmonary artery, used either as inflow for left ventricular venting or as outflow for right ventricular mechanical circulatory support, are easily and rapidly deployable with transesophageal and fluoroscopic guidance.

Methods

We chose to review our institutional and technical experience with all right atrium to pulmonary artery cannulations.

Results

Based on the review we describe six right atrium to pulmonary artery cannulation strategies. They are divided into total right ventricular assist support, partial right ventricular assist support, and left ventricular venting. A single limb cannula or a dual lumen cannula can be used for right ventricular support.

Conclusions

In the right ventricular assist device configuration, percutaneous cannulation may prove beneficial in cases of isolated right ventricular failure. Conversely, pulmonary artery cannulation can be used for left ventricular venting as drainage to a cardiopulmonary bypass or extracorporeal membrane oxygenation circuit. This article can be used as a reference for the technical aspects of cannulation, decision-making in patient selection, and management of patients in these clinical scenarios.

Key Words: RVAD: Right Ventricular Assist Device, ECMO: Extracorporeal Membrane Oxygenation, acute RV failure: Acute Right Ventricular Failure, mechanical circulatory support: Mechanical circulatory support, LV Venting

Introduction

Percutaneous cannulas that are placed from the femoral vein or the internal jugular vein to the pulmonary artery (PA) can be used either as inflow to an extracorporeal circuit as a left ventricular (LV) vent or as outflow for right ventricular assist device (RVAD) configuration. They are easily and rapidly deployable with transesophageal and fluoroscopic guidance. In experienced centers they can be deployed at the bedside. The indication for percutaneous cannulation of the PA are twofold; i) acute RV failure or ii) LV venting due to LV distension.

Acute Right Ventricular Failure
Acute RV failure is defined as a rapidly progressive syndrome with systemic congestion resulting in impaired filling of the right ventricle (RV), reduced RV cardiac output, and uncoupled pulmonary artery pressures.\textsuperscript{4-6} It is associated with elevated RV afterload or preload with impending liver and renal failure. It manifests as RV dilation, RV systolic failure, and tricuspid regurgitation. Typically, the central venous pressure is elevated and the pulmonary artery pressures can be elevated. Renal and liver function also decline in the setting of venous congestion and poor forward flow.\textsuperscript{4-6} Acute mechanical circulatory support may be required to rescue acute RV failure refractory to medical management.\textsuperscript{6,7} Invasive options include atrial septostomy, micro-axial intracorporeal rotary pump devices, and extracorporeal mechanical circulatory support. Percutaneous RVAD devices connected to an extracorporeal centrifugal pump are an alternative to surgical, centrally cannulated RVADs. Advances in cannula design, ease of bedside placement, and ability to remove at the bedside have allowed percutaneous RVAD devices to become an increasingly used strategy for RV support.\textsuperscript{8} The most important factor in having a successful outcome in patients with acute RV failure is timing of mechanical circulatory support.\textsuperscript{2} Late deployment is universally associated with poorer outcomes.\textsuperscript{9} Percutaneous RVADs can be combined with oxygenators as veno-pulmonary extracorporeal membrane oxygenation (ECMO) when simultaneous acute RV failure and respiratory failure occurs.

Left Ventricular Venting

Left ventricular (LV) venting is necessary in several conditions during cardiopulmonary bypass (CPB) or peripheral Venoarterial (VA) ECMO.\textsuperscript{10} Both surgical and percutaneous options exist for LV venting. Typically, LV venting is indicated when LV distention occurs. LV distension is associated with increased LV wall stress, increased risk of myocardial ischemia and can lead to decreased chances of LV recovery. The most common surgical LV venting strategy during CPB is by using a soft flexible catheter placed from the right upper pulmonary vein through the mitral valve into the LV. However, alternative surgical venting sites include the LV apex and the PA. Likewise, for patients on peripheral VA ECMO, strategies for LV venting include placing a micro-axial pump device (Impella, Abiomed Danvers, MA) through the aortic valve, indirect venting with an intra-aortic balloon pump which improves LV function and thereby improves RV function, or direct surgical LV apical venting via mini-thoracotomy. Percutaneous PA venting is a reasonable option with benefits which include the ability to place and remove at the bedside. In this setting, percutaneous PA cannulas spliced into the inflow limbs of CPB or VA ECMO can be deployed for LV venting. There are two main limitations of indirect LV venting through the PA. First, indirect LV venting is not always ideal in the longer term ECMO setting. There are typically two phases to LV recovery, the immediate full support VA ECMO shock state and the later LV recovery phase. In the peripheral VA ECMO setting, with LV recovery low flow ECMO is optimal because it is associated with less LV afterload from retrograde pressure. However, if a PA vent is chosen for LV distension, then ECMO flows typically have to be high for venting and to prevent LV distension. In this setting the PA vent may result in hindering LV recovery due to increased afterload. Second limitations occur with valvular insufficiency. In an incompetent mitral valve will also prevent improved recovery because blood will then drain into the PA vent retrograde. In these situations, a direct surgical vent or percutaneous micro-axial LV vent may be more optimal. Alternatively, as LV recovery is occurring then the PA vent can be converted to an RVAD providing forward flow and RV...
protection. Therefore, a PA vent may be more ideal in the acute setting or the cardiopulmonary bypass setting, however conversion should be considered if longer term LV decompression is needed or if the LV is recovering.

Percutaneous Pulmonary Artery Cannulation

Recently, Shah et al. discussed hybrid and parallel ECMO circuits. In their report they described several atypical extracorporeal configurations. In this report, we extend the concept of complex extracorporeal circuitry beyond the basic peripheral venovenous (VV) and VA ECMO circuit and describe technical aspects of percutaneous PA cannulation. Furthermore, we describe both our institutional perspective as well as unique uses of this cannulation configuration such as indirect venting in ischemic VSD, indirect venting with peripheral VA ECMO, double outflow venovenopulmonary ECMO, as well as the traditional dual lumen cannula (DLC) oxy-RVAD cannulation.

Technical Considerations

Cannulation

Planning for PA cannulation revolves around vascular access assessment and focused echocardiography. In order to percutaneously access the femoral vein or internal jugular vein surface ultrasound should be used to assess the vessel caliber and patency. Patients who require percutaneous PA cannulation may often have limited vascular access secondary to prior access, in situ cannulas, or central venous thrombosis. Additionally, transthoracic or transesophageal echocardiography should be used to assess the tricuspid and pulmonic valve structure and function. The tricuspid annulus diameter should be measured and the regurgitation should be rated according to the American Society of Echocardiography guidelines. Furthermore, assessment of right atrium (RA), RV, and PA should be analyzed and documented. Presence of pacing wires, tricuspid valve replacement or rings, clots or thrombus may prevent successful percutaneous RVAD placement. The patency of the superior vena cava and caliber can be assessed with contrast injection venogram or digital subtraction venography at the time of cannulation. If there is narrowing then superior vena cava (SVC) syndrome may occur with the larger caliber DLC resulting in obstructing upper body venous inflow and smaller cannulas should be selected.

Once ready for cannulation, the patient should be prepared and draped in standard fashion. The head should be secured in midline position and draping should provide access to both sides of the neck as well as bilateral groins. Occasionally, the left internal jugular vein can be used for access. We have found that if the internal jugular vein is not accessible then the supraclavicular approach to the subclavian vein (SCV) is also a viable option. Although a non-traditional access location, the advantage of the supraclavicular approach to the SVC is that after decannulation direct manual pressure can be applied in this location as opposed to the traditional infraclavicular approach to the SCV. It should be noted that if an alternative upper body site for cannulation is used, then the operator may encounter difficulty navigating the turn from the SCV/Internal Jugular (IJ) to right innominate vein confluence or the left innominate vein to SVC confluence. Alternatively, femoral approaches to the PA have also been used. Tandem Life (Livanova, UK)
cannulas from the femoral vein have been used to access the PA; however, in recent years with the advent of newer lower profile neck cannulas, femoral access to the PA has dwindled. Finally, the chest should be prepared into the field in case of catastrophic bleeding due to tamponade or PA injury. Percutaneous or surgical drainage of pericardial bleeding may be necessary in this circumstance.

Cannulation distally beyond the SVC requires both fluoroscopy and transesophageal echocardiography. Typically, a free-floating C-arm or fixed C-arm fluoroscopy suite is required for anterior-posterior imaging during percutaneous RVAD placement. After obtaining vascular access a 7 French balloon tipped Arrow (Teleflex, NC) flow directed catheter is navigated to the right PA. Using this catheter, the RA, RV, PA systolic, PA diastolic, and pulmonary capillary wedge pressures can be transduced and recorded. Using this same catheter, contrast can also be injected, if necessary, to assess the caliber of the SVC, locate the position of the tricuspid valve or location of the PA bifurcation. (Image 1) When ready for cannulation, the catheter is positioned just distal to the overlap of the SVC and PA on fluoroscopy such that the catheter crosses itself on the 2D image. (Image 2) It is important to note that alternative catheters and techniques may be necessary to traverse the tricuspid valve (TV) if there is a tricuspid ring or replacement in the TV position. If there is difficulty floating a balloon tipped catheter across the TV, a Judkins right catheter or a multipurpose catheter can be used to engage the TV orifice and then a soft wire such as a Glidewire can be used to traverse the TV into the RV. If percutaneous RVAD placement is done with an open chest, the sternal retractor may need to be removed for imaging, with manual palpation used as a last resort to redirect a catheter from the RV apex to the RV outflow tract.

Once the balloon tipped catheter is in the right PA, a 260 cm Extra-stiff Amplatz or 260 cm Lunderquist wire with a 4 cm straight floppy tip (Cook Medical, Bloomington, IN) is advanced through the catheter. (Image 2) Care is taken that the wire is not extended too far distally and thereby injuring the smaller segmental pulmonary artery vasculature. After serial dilation of the insertion site with a Sorin dilator kit (Livanova, UK), an PA cannula of choice is passed over the wire and the distal tip is positioned into the right PA. Loforte et al. in their case report, describe an alternative method of placing an PA venting cannula. In their method, they first access the internal jugular vein and place a wire into the RA. They then dilate the skin tract and place the cannula into the RA. They, then subsequently float a balloon tipped Swan-Ganz catheter through the back end of the cannula to the PA. Finally, they use the swan as a rail to the PA.15

It is important to confirm the position of the distal tip of the cannula. Under fluoroscopy it may be difficult to decipher the subtle edge of the cannula in contrast to the dilator. The inner dilator should be retracted back to the distal edge of the cannula under fluoroscopy to confirm the final position of the cannula. If, inadvertently, the cannula is retracted back to the subpulmonic position it is not advised to blindly advance the cannula into the main PA without a wire or dilator. If the cannula is mispositioned, it will need to be completely removed and the balloon tipped catheter floated to the right PA once more. Unfortunately, if this occurs a large dilated skin tract exists and a large sheath introducer may need to be placed at the entry site while reflating the balloon tipped catheter to abate the venous bleeding at the level of the skin. It is advised that the cannula be initially placed into the right PA or left PA and then the extracorporeal pump flows maximized. The RV size will reduce with increased offloading and
decompression of the RV as well as improve the LV geometry. As the process occurs there is a tendency of the cannula to migrate back at full flow RVAD support. Only when full flow is achieved should the cannula be retracted back into final location in the main PA to ensure that the cannula does not inadvertently migrate subpulmonic. Importantly the cannula should be secured to posterior to the ear to the occiput to ensure minimal movement in an awake extubated patient.

Echocardiography should be used in tandem with fluoroscopy for final positioning. 2D imaging as well as color doppler is required to ensure equal blood flow to both right and left PA. Cannula flow if directed unilaterally may result in lung hyper-perfusion, edema, and pulmonary hemorrhage.

**Cannula Selection**

Cannula selection depends on the institutional resources available and the cannulation strategy planned. There are four main percutaneous cannula options. Cannula diameters range from 17 French to 31 French and should be typically 50 cm or longer.

The first two options are DLC which include the Protek Duo cannula made by Livanova ® (London, England) and the Spectrum cannula made by Spectrum Medical ® (Cheltenham, England). A DLC is a cannula that contains both two lumens in a single device. The proximal orifice for these cannulas is located in the RA and the distal orifice is in the PA. The two lumens can be used both as inflow, both as outflow, or one as inflow and the other as outflow. The Spectrum cannula is unique because it is designed as a dual stage DLC with inflow holes extended down to the RV. This increases the chances of fully unloading the RV. This however requires the full outer diameter of the cannula to traverse the TV. Furthermore, the Spectrum cannula relies solely on the competency of the pulmonary valve (PV) to prevent recirculation whereas the Protek Duo cannula has both the TV and PV in between the two separate orifice zones. The outer diameter of the largest cannula is 31Fr cannula; however, it is important to remember the distal PA lumen is effectively 15Fr and therefore limited to flows <3.7 L/min in order to avoid excessive line pressures above 200 mmHg and subsequent hemolysis.

A third percutaneous PA cannula type is a single lumen, end-hole Next-Gen Biomedicus (Medtronic, MN) venous cannula. This cannula can be used as inflow to an extracorporeal circuit as venting or as an outflow from the extracorporeal circuit. The advantage of using an independent cannula, as opposed to the DLC cannulas, is having a larger distal PA cannula size for optimal flow (Fr size 17 – 21) as well calibrating the size to the indication for support. If using this cannula in the RVAD configuration a separate femoral venous inflow cannula is needed. This inflow drainage cannula can be optimally positioned in the mid RA. One of the limitations of the DLC cannulas in the RVAD configuration is that the inflow orifice can be overlying the SVC or TV depending on patient size or RV size and this may result in repeated suck down events or valvular injury. This may consequently result in less than desired flow rates. An independent two cannula set up will allow for optimal inflow with the cannula positioned in the mid RA as well as little flow resistance in the outflow limb. Second, due to the smaller overall size of the cannula (17 – 21 Fr versus 29 – 31 Fr) there is a decreased risk of SVC syndrome. 12,13
The final cannula option is a single lumen long multi-orifice cannula as drainage from the PA and RV for LV venting. In unique situations such as in CPB or peripheral VA ECMO, LV venting is critical to prevent LV distension, LV ischemia and promote recovery. Placing a percutaneous multi-orifice cannula from the internal jugular vein to the PA and then splicing this into the inflow circuit for CPB or VA ECMO is feasible. It is important to note that both DLCs (Protek Duo or Spectrum Dual-Lumen), the single lumen end hole Biomedicus venous cannula, or multi-orifice cannulas can be used as PA and RV drainage. The advantage of using these other cannulas for drainage as opposed to the multi-orifice long single lumen cannula for drainage is that these cannulas can be used in a staged fashion. This means that if the cannulas are used upfront during CPB or VA ECMO for venting they can later be reversed as outflow for RVAD support.

Configurations

Creative inflow and outflow methods have been described using a various number of cannulation configurations from the RA to PA. Here we describe six configurations for RA to PA cannulation either as inflow, outflow or both. (Image 3) It is imperative clinicians understand extracorporeal nomenclature. The ELSO Maastricht Treaty for ECLS nomenclature can be used to describe the six main RA to PA configurations.

RVAD

1. Two independent cannulas (Image 3, Figure A) (Table 1, Strategy 1)

In this configuration an independent multi-orifice venous cannula is positioned in the mid RA as inflow from the femoral vein and a second independent end hole Biomedicus Venous (Medtronic, Minneapolis, MN) cannula 17 – 21 French is placed from the IJ to the PA as outflow. (Image 3, Figure A) (Table 1, Strategy 1) If there is no oxygenator in line, in an RVAD only configuration, this strategy is labeled as VRAXP RVAD. If there is an oxygenator inline then this configuration is called VRAXP ECMO. Historically, the Tandem percutaneous RVAD (Livanova, UK) was a similar configuration except that the inflow cannula originated from the left femoral vein and extend the RA and the outflow cannula originated from the right femoral vein and extended to the PA. This configuration severely limits mobility with bifemoral cannulation.

2. DLC – Protek Duo/Spectrum (Image 3, Figure B) (Table 1, Strategy 2)

In this configuration a single DLC is positioned with tip in the PA and inflow orifice in the RA +/- RV. (Image 3, Figure B) This is classified as (dlc) VRAXP (Protek Duo) or (dlc) VRAXPRV x P (Spectrum) if there is no oxygenator inline. If there is an oxygenator in line configuration is called (dlc) VRAP - P (Protek Duo) or (dl) VRAPRV - P (Spectrum)

Partial RVAD
3. Double outlet (Can only be constructed with Protek Duo) *(Image 3, Figure C) (Table 1, Strategy 3)*

In this configuration an independent multi-orifice femoral vein cannula positioned in the IVC is used as inflow to the pump and both limbs of a Protek Duo cannula are used as oxygenated outflow using a Y-connector. *(Image 3, Figure C) (Table 1, Strategy 3)* This configuration is used to limit excessive continuous direct blood flow into the PA. This configuration when used with an oxygenator is called \( V_{IVC} - (dlc) V_{RAP} \) (Protek Duo ECMO). A Hoffman clamp is necessary on the \( V_{RA} \) limb to calibrate flow between the two outflow limbs. This configuration can only be constructed with the Protek Duo cannula. The Spectrum Dual stage DLC has orifice holes that are in the RV and therefore, this limb can only be used for inflow, and cannot be used for outflow.

4. PA bridge (Biomedicus or Protek Duo) *(Image 3, Figure D) (Table 1, Strategy 4)*

This is a very unique configuration and has been tried at a select few centers. It mimics percutaneously, the surgical Dembitsky bridge. This cannulation configuration can be used in patients with pulmonary arterial hypertension or in patients with aortic root hypoxia on VA ECMO with RV failure to offload some of the PA flow to the systemic circulation yet provide oxygenation to the aortic root in the setting of a failing RV. *(Image 3, Figure D) (Table 1, Strategy 4)* In this configuration a multi-orifice femoral vein cannula is positioned in the mid RA and a 15 – 17 Fr cannula is placed in the femoral artery and a single lumen venous long end hole cannula is placed in the PA. The outflow from the ECMO circuit is bifurcated with a Y-connector and both the femoral arterial (FA) and PA cannulas are oxygenated. *(Image 3, Figure D) (Table 1, Strategy 4)* This configuration can also be constructed by using a DLC Protek Duo cannula and using the RA limb as inflow and then using the PA limb and a separate 15 – 17 Fr FA cannula as an outflow. In this configuration this is called \( (dlc) V_{RA} - (dlc) A_{FP} \). A Hoffman clamp is also necessary to calibrate flow between the PA and the FA.

**LV Venting**

5. Total Drainage Single Lumen Multi-orifice cannula in PA in VA ECMO *(Image 3, Figure E) (Table 1, Strategy 5)*

By using the RV to PA cannulation techniques, a multi-orifice cannula intended typically for the femoral vein to IVC or RA can be placed from the internal jugular vein and placed into the PA. The multi-orifice drainage can therefore decompress the PA, RV and RA depending on the distance from the first to last inflow holes. *(Image 3, Figure E) (Table 1, Strategy 5)* This cannula can be used independently or in conjunction with a separate femoral venous to IVC/RA cannula. When used as an independent cannula this would be called \( P_{RV} - A \) ECMO (Single Drainage) or when used with two separate cannulas \( V_{RA/IVC} P_{RV} - A \) ECMO (Dual Drainage)

6. Reversible VA ECMO to RVAD. DLC Protek Duo or Spectrum as Inflow or Two cannula with Single Lumen End Hole in PA – Biomedicus as drainage. *(Image 3, Figure F) (Table 1, Strategy 6)*
In cases where there is anticipated LV recovery a single lumen end-hole cannula or Protek Duo/Spectrum Dual-Lumen can be used as ECMO inflow with an outflow placed into the femoral artery. When the LV recovers, if there is residual acute RV failure then the femoral artery can be decannulated and the in-situ cannula can be converted as an RVAD (Category 1 or 2). This can be done with a Biomedicus venous long end hole cannula as \( V_{\text{RA/IVC}} - \text{A} \) or with a DLC Protek Duo or Spectrum Cannula as \( V_{\text{RAP}} - \text{A} \) Protek Duo or \( V_{\text{RARV}} - \text{A} \) Spectrum. (Image 3, Figure F) (Table 1, Strategy 6)

**Conclusion**

Multiple different configurations for percutaneous RVAD support as well as PA venting are possible. In patients with medically refractory RV failure, mechanical circulatory support is indicated. Extracorporeal pumps with associated cannulas can provide RV support in conditions post durable left ventricular assist device surgery, in acute RV infarction, or in cases with RV failure in acute respiratory distress syndrome. Likewise, placing a percutaneous PA cannula, with the same technique can be used for indirect LV venting during CPB or VA ECMO.
Image 1:

Fluoroscopic imaging of the SVC for caliber and sizing for cannula deployment as well as location of the PA bifurcation.
Image 2:

Wire guidance through the flow directed balloon tipped catheter was well as advancement of the percutaneous PA cannula

Image 3:

Figure A: RVAD with two independent cannulas
Figure B: RVAD with Dual Lumen Cannula
Figure C: Double outlet VV ECMO + Partial RVAD with double outflow
Figure D: V-PA ECMO, VA ECMO with Partial RVAD Percutaneous bridge
Figure E: Total Venous drainage
Figure F: LV Venting with reversible RVAD
Table 1:

<table>
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<th>Strategy</th>
<th>Inflow Cannula</th>
<th>Inflow Location</th>
<th>Outflow Cannula</th>
<th>Outflow Location</th>
<th>Simple Name</th>
<th>ELSO Nomenclature</th>
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<td>1 RVAD Two independent</td>
<td>Femoral Vein to RA Multiorifice drainage cannula 25 Fr Medtronic</td>
<td>RA/IVC</td>
<td>17 – 21 Fr single lumen long end hole cannula</td>
<td>Main PA</td>
<td>V-P RVAD V-P ECMO</td>
<td>V_{RA x P RVAD} V_{RA – P ECMO}</td>
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<td></td>
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<td>RA – Protek Duo RA + RV - Spectrum</td>
<td>15.3 French Second limb of DLC Protek Duo 15.5 French Second limb of DLC Spectrum</td>
<td>Main PA</td>
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<td>(dlc) V_{RA x P (Protek Duo RVAD)} (dlc) V_{RA/RV x P (Spectrum RVAD)} (dlc) V_{RA - P (Protek Duo ECMO)} (dlc) V_{RA/RV - P (Spectrum ECMO)}</td>
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<td>IVC</td>
<td>Both limbs of the Protek Duo cannula</td>
<td>RA + PA Clamp applied to titrate flows</td>
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<td>V_{IVC} - (dlc) V_{RAP (Protek Duo ECMO)}</td>
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<td>2 RVAD DLC</td>
<td>Femoral Vein to RA Multiorifice drainage cannula 25 Fr Medtronic</td>
<td>RA +/- IVC +/- RV</td>
<td>15 – 17 French Femoral Arterial + 17 – 21 French single lumen Biomedicus or Distal limb of Protek Duo or Spectrum Cannula</td>
<td>FA + PA Clamp applied to titrate flow to PA and FA based on the systemic circulation pressure and pulmonary circulation pressure</td>
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<td>VP-A ECMO</td>
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<td>FA</td>
<td>VP-A ECMO</td>
<td>P_{RV} – A ECMO (Single Drainage)</td>
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<td>With or without a separate single lumen femoral vein to RA multiorifice inflow cannula</td>
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<td>V_{RAIVC}P_{RV} – A (Double Drainage)</td>
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<td>6</td>
<td>LV Venting with Reversible VA ECMO to RVAD</td>
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