VADs and ECMO Workshop

Congenital Cardiac Anesthesia Society Annual Meeting
Colorado Springs, CO
March 31, 2016
Warwick Ames, MD; Katie Butler, RN; Craig McRobb, CCP

Conflict of interest:
None
At the end of this workshop, the participant will be able to:

• Demonstrate how an extracorporeal membrane oxygenation (ECMO) machine works and explain different ECMO techniques.

• Demonstrate how ventricular assist devices (VAD) work and how they may be applied to different clinical scenarios.

• Discuss the anesthetic implications of ECMO and VAD.
Workshop Format

• Welcome and brief introductions (Wads)

• ECMO and VAD overview (presentation – Craig)

• Breakout into 3 stations (20 mins each)
  ▪ Craig – VAD hands-on (Berlin Heart, Centrimag, Heartware, Heartmate II, Heartmate XVE, Thoratec PVAD)
  ▪ Katie – ECMO (CardioHelp)
  ▪ Wads – Anesthesia concerns for the ECMO/VAD patient (powerpoint with Q and A)

• Re-convene the entire group for closing Q and A
Terminology

- Ventricular assist device = VAD
  - Blood pump which replaces function of ventricle only
- Types of VAD
  - LVAD, RVAD, BiVAD
  - Temporary vs. Durable
- ECMO = VAD plus oxygenator
What does ECMO Provide?

• Gas Exchange
  ▪ Oxygenation of the blood
  ▪ CO2 removal

• Cardiac Output
  ▪ ECMO Flow + Patient Stroke Volume
# Conditions supported by ECMO

<table>
<thead>
<tr>
<th>NICU</th>
<th>PICU</th>
<th>CICU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent Pulmonary Hypertension (PPHN)</td>
<td>Sepsis</td>
<td>Congenital Heart Disease (CHD)</td>
</tr>
<tr>
<td>Meconium Aspiration Syndrome (MAS)</td>
<td>Pneumonia</td>
<td>Myocarditis</td>
</tr>
<tr>
<td>Congenital Diaphragmatic Hernia (CDH)</td>
<td>Asthma</td>
<td>Cardiomyopathy</td>
</tr>
<tr>
<td>Sepsis</td>
<td>Trauma</td>
<td>Post-op cardiac repair</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>Aspiration</td>
<td>Bridge to Transplant</td>
</tr>
<tr>
<td>Neonatal Respiratory Distress Syndrome</td>
<td>Ingestion</td>
<td>Cardiogenic shock</td>
</tr>
<tr>
<td></td>
<td>Septic Shock</td>
<td>Arrhythmias</td>
</tr>
<tr>
<td></td>
<td>Acute Respiratory Distress Syndrome (ARDS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H1N1</td>
<td>Pulmonary Hypertension</td>
</tr>
</tbody>
</table>
Patient Selection Criteria

- Potentially reversible disease process
- Absence of significant irreversible end-organ failure
- Absence of uncontrolled bleeding within major organs
- Absence of severe intracranial pathology

AND

- Escalating ventilator support and/or hemodynamic support is ineffective and causing more damage
Adjustable ECMO Variables

- **RPMs (ECMO Flow)**
  - LPM or ml/kg/min blood flow
    - Flow is dependent on:
      - Preload
      - Afterload

- **FiO₂**
  - Concentration of oxygen flowing through the oxygenator

- **Sweep**
  - LPM flow through oxygenator
  - Removes carbon dioxide

- **Hemofiltration**
  - Fluid removal via artificial kidney

- **Temperature**
Two Types of ECMO

Veno-arterial (VA)

Veno-venous (VV)

Interchopen.com
VA ECMO

- Most commonly used MCS device in pediatric population (mostly respiratory)
- Short to long term??
- Cheap (circuit, not management)
- **Rapid deployment** in cardiac arrest situations → ECPR
- Complete (partial) cardio-respiratory support
  - Allows lungs/ventricles to rest and recover,
  - Wean inotropes, reduce vent settings (avoid lung injury), stabilize patient – create physiologic environment that allows healing and treatment a chance to work
  - Hopefully prevents multi organ failure
- Complicating Factors:
  - Complex and large (poorly portable) system
  - Requires anticoagulation
  - Often requires frequent transfusions for hemolysis
  - Often requires intubation + mechanical ventilation.

VA ECMO
VA ECMO Circulation

Deoxygenated blood removed from the right atrium via a venous cannula

ECMO circuit (blood oxygenated, CO2 removed, blood warmed)

Oxygenated blood returned via an arterial cannula into the aorta

Oxygenated blood circulated to tissues and organs
VA ECMO

**Advantages**
- Provides full cardiopulmonary support
- No mixing of arterial / venous blood
- Good oxygenation at low ECMO flows
- Allows for total lung rest

**Disadvantages**
- Possible ligation of the right carotid artery
- Non-pulsatile arterial blood flow may lead to renal insufficiency
- Suboptimal conditions for LV function
  - Low preload
  - High afterload
  - High wall stress
  - Poor coronary oxygenation
• Pulmonary support only, no direct cardiac support (indirect support)
  ▪ Requires normal cardiac function
• Indication: pulmonary failure
  ▪ Unresponsive to multiple different modes and ventilation strategies
• Set up:
  • Same circuit as VA attached to patient differently
  • One large dual lumen cannula provides drainage and reinfusion
  • Oxygenates venous blood which is pumped to lungs (decreased PVR)
  • Often done in cath lab with fluro/echo guidance
• Allows vent settings to be reduced and lungs to heal or be treated
Deoxygenated blood removed from a combination of the right atrium, SVC and IVC via a venous cannula

ECMO circuit (blood oxygenated, CO2 removed, blood warmed)

Oxygenated blood returned to the right atrium

Mixes with desaturated systemic blood

Partially oxygenated blood circulated to lungs

Returns to the left side of the heart and then to the body
Advantages

- Provides pulmonary gas exchange
- Provides the normal pulmonary circulation with oxygenated blood
- Avoids carotid artery ligation
  - Less risk of stroke
- Normal pulsatility
- Eliminates the problem of venous blood perfusing the coronaries
- Can be converted to VA if necessary
- Can support the patient for an extended period of time

Disadvantages

- No direct circulatory/cardiac support
  - If the patient’s heart fails to provide the necessary support, the patient may require a second surgery to convert to VA
- Oxygenation is lower than with VA ECMO because of the mixing of oxygenated returned blood with desaturated systemic venous blood

<table>
<thead>
<tr>
<th>Circuit ABG</th>
<th>Patient ABG</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.41</td>
</tr>
<tr>
<td>pCO₂</td>
<td>38 mmHg</td>
</tr>
<tr>
<td>pO₂</td>
<td>430 mmHg</td>
</tr>
<tr>
<td>HC0₃</td>
<td>25 mEq/L</td>
</tr>
<tr>
<td>Base Excess</td>
<td>0.4</td>
</tr>
<tr>
<td>Saturation</td>
<td>100 %</td>
</tr>
<tr>
<td></td>
<td>7.42</td>
</tr>
<tr>
<td></td>
<td>42 mmHg</td>
</tr>
<tr>
<td></td>
<td>60 mmHg</td>
</tr>
<tr>
<td></td>
<td>25 mEq/L</td>
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<tr>
<td></td>
<td>- 0.8</td>
</tr>
<tr>
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<td>91 %</td>
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</tbody>
</table>
## VA vs. VV ECMO

<table>
<thead>
<tr>
<th></th>
<th>VA</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cannulation Sites</strong></td>
<td>IJ or femoral vein, RA; Common carotid, aorta</td>
<td>DLC-IJ; multi site- IJ or femoral vein</td>
</tr>
<tr>
<td><strong>Circulatory Support</strong></td>
<td>Partial to complete</td>
<td>No direct; possible indirect</td>
</tr>
<tr>
<td><strong>Oxygen Delivery Capacity</strong></td>
<td>High</td>
<td>Moderate to High</td>
</tr>
<tr>
<td><strong>Cardiac Effects</strong></td>
<td>↓ preload, ↑ afterload, Cardiac stun possible</td>
<td>Negligible direct; indirect-may improve coronary oxygenation, may ↓ right ventricular afterload</td>
</tr>
<tr>
<td><strong>Effect on pulmonary circulation</strong></td>
<td>Moderate to markedly decreased</td>
<td>Unchanged or improved with oxygenated blood</td>
</tr>
</tbody>
</table>
ECMO Complications/Emergencies

- Bleeding
- Stroke
- Blood Clots
- Infection
- DIC (Disseminated Intravascular Coagulation)
- HIT (Heparin Induced Thrombocytopenia)
- Transfusion related reactions
- Air in Circuit
- Mechanical failure/malfunction
- Death
Ventricular Assist Device (VAD)

- A mechanical pump that typically is surgically attached (directly/indirectly) to one or both of the heart’s ventricles.
- Unloads the ventricle(s):
  - Reduces wall tension and myocardial O2 demand
  - Increases O2 supply (systemic and coronary)
  - Reduces inotrope dependence
  - **Allows heart to rest and recover** or supports patient until transplant
- Can be used for the left (LVAD), right (RVAD), or both ventricles (BiVAD)
- Driven by external power sources that connect to the pump via a percutaneous lead that exits the body through the skin (implantable electric pumps) or driven by pneumatic driveline
- VAD flow can be pulsatile or nonpulsatile
  - Berlin Heart vs. CMAG
VAD vs. ECMO

**ECMO**

- ECMO provides both blood flow and oxygenation (cardiac and pulmonary support)
- Short term (long term is possible today)
- Relatively cheap

**VAD**

- VAD provides blood flow only (cardiac support)
  - Patient must have adequate lung fx or have oxygenator in circuit
- Short-Long term
- Expensive
Indications

- Bridge to transplant (BTT)
  - most common
  - allow rehab from severe CHF while awaiting donor

- Bridge to recovery (BTR)
  - unload heart, allow “reverse remodeling”
  - can be short- or long-term

- “Destination” therapy (DT)
  - permanent device, instead of transplant
  - currently only in transplant-ineligible patients

- Bridge to candidacy (BTC)/Bridge to decision (BTD)
  - when eligibility unclear at implant
  - not true “indication” but true for many pts
Conditions

• Cardiomyopathy
  ▪ Various etiologies
• Myocarditis
• Post-cardiotomy
VAD Classifications

- Pulsatile vs. Non-Pulsatile
- Internal vs. External (Intracorporeal vs. Paracorporeal)
- Electric vs. Pneumatic
- Short term vs. Long term
- Percutaneous vs. Direct cannulation
Typical Cannulation Sites

• RVAD inflow
  ▪ Femoral vein, RIJ, right atrium

• RVAD outflow
  ▪ Pulmonary artery

• LVAD inflow
  ▪ Left atrium, LV apex

• LVAD outflow
  ▪ Aorta, femoral artery
Key Concepts

• VADs are preload dependent and afterload sensitive
  ▪ Preload and afterload management

• If patient has only LVAD, **must continue to support the right heart** (inotropes, pacing/antiarrhythmia meds, nitric oxide, milrinone) since the right heart must provide blood flow to the LVAD
  ▪ If patient has arrhythmia you must defibrillate/cardiovert/pace etc.

• With BIVAD, above situation is not a big concern
  ▪ May need to adjust RVAD parameters to get better filling on the LVAD, and vice versa (LVAD ultimately feeds RVAD)
  ▪ Keep RVAD flow lower than LVAD flow (pulm edema/hemorrhage)
Determining Which MCS Device

- Support type?: Cardiac + respiratory vs Cardiac only vs Resp only
- Support speed?: Rapid response vs non-rapid response
- Support duration?: Long term vs short term
- Patient size?: 2kg - 200kg
- Device availability?
- Transport device?
- May change MCS device as patient condition changes
  - Lungs heal but LV still not recovered
  - Adding a short term RVAD device to someone on a long term LVAD
When the Lungs Fail on VAD Support

• Unusual cases
  ▪ Berlin Heart BiVAD converted to ECMO, then back to Berlin Heart
  ▪ Different VAD types on each side
  ▪ VADs as vents
Anesthesia for ECMO/VAD’s

- ECMO is the mainstay of mechanical support but is limited
- VADS offer long term support, freedom from sedation and mobility
- Better outcomes with VAD than ECMO as a Bridge to Transplantation.
- Donor organ deprived system.
- Population of children requiring anesthesia for:
  - ECMO deployment
  - VAD insertion
  - Non cardiac surgery / interventions
- Key issues are:
  - Call perfusion
  - Volume / SVR.
Anesthesia For ECMO

- Who is responsible for sedation/ anesthesia
- Akin to CPB
Which VAD?

- At Duke:
  - Newborns / infants Berlin Heart Cannulae and a PediMag.
  - Transitioned to a Berlin heart
  - Older Children, 60kgs and above, get a HeartWare (MVAD).
  - Jarvik/PumpKIN will be compared against Berlin in kids between 8-15 kg in a randomized trial.
Anesthesia for VAD placement

• Preoperative evaluation:
  ▪ Overt or occult end organ dysfunction.
  ▪ Renal: GFR<60ml/min·1.72m² is a risk factor for renal failure.
  ▪ Hepatic: LFT’s and coagulation profile
  ▪ B-Natriuretic peptide (BNP) as an indicator for elevated Ventricular EDP
  ▪ Recent echo and Cardiac catheterization results (clues for vascular access)
  ▪ Pacemakers/ICD should be reprogrammed (magnet not acceptable)
  ▪ Blood bank: Alert for massive transfusion. Consider cross match may be difficult, Leucocyte depleted products needed, CMV free blood if the patient is CMV negative
Induction and prebypass Mx

- Standard monitoring with Aline/CVP
- Echocardiography: to exclude PFO or other intracardiac shunts/ significant Aortic regurg/ TVR/ MS/ thrombi etc.
- Induction should blunt hemodynamic response to intubation without myocardial depression, vasodilation and subsequent hypotension. (Dilated Cardiomyopathy patients have down regulated B receptor function and reduced norepi stores so myocardial depressant effects of induction agents, will be keenly noted.)
- Preoperative inotropes should be continued
- Initiation of Positive pressure ventilation will likely be asc with significant pulse pressure variation, so careful titration of appropriate ventilation should be initiated
- Hypoventilation/atelectasis will ↑ PVR
- Monitor serum lactate and mixed venous oxygen saturations.
Separation from Bypass

- Echocardiography to assess inflow cannula position, native heart valve and ventricular function, intra-cardiac air, and volume status.
- LVAD requires sufficient intravascular volume and RV function to fill the pump.
- RV function must match the combined LV and LVAD output.
- LVAD insertion alone, decreases RV function with decompression of the LV and loss of the leftward septal shift.
- Generally MVR improves and TVR worsens.
- Pulmonary vasodilators may be needed (milrinone and nitric oxide) and inotropes may be required for RV dysfunction.
- Tricuspid valvuoplasty may be required if TVR persists. If that fails- ECMO or BiVAD.
Centri / Pedi Mag

- Short term device. A rotary (or centrifugal pump)
- ECMO is poor at decompressing the LV which may be even worse in CHD with increased cardiac return (systemic pulmonary collaterals). Adequate decompression will aid LV recovery.
- Basically ECMO without an oxygenator
- Extracorporeal so plasma exchange/hemodialysis can easily be added
- Typically Berlin Heart Cannula in place and centri / Pedi mag used until Thrombus risk is less. Then convert to Long term EXCOR Berlin Heart.
- Only VAD that actually measures ‘Flow’
Anticoagulation

• Most VAD complications are either thrombosis (30%) or bleeding (60%).
• Suppression of coagulation and platelet function occurs acutely after device implantation but is followed by hypercoagulation state requiring anticoagulation and platelet inhibition.
• Blood products are needed in abundance. Factor VII may be necessary and has been well reported (not FDA approved)
• Heparin must be fully reversed and surgical bleeding addressed. Restart heparin later (target Anti-Xa 0.35-0.5)
• We have noted at Duke that elevating the Antithrombin III levels to 100% plus has reduced the need for Heparin, in some cases entirely… check this
• TEG (ROTEM) / Platetet count/ PT/PTT/ Fibrinogen levels
**Edmonton Protocol**

| Perioperative                                                                 | Chronic                                                                 |
|----------------------------------------------------------------------------|
| Baseline coagulation studies, TEG, and thrombophilia screen                | anti-Xa 0.6–1.0                                                         |
| Complete heparin reversal coming off CPB                                   | ADP net G 4–8                                                           |
| Low-dose heparin initiated after surgical haemostasis                      | AA inhibition > 70%                                                     |
| (target anti-Xa 0.35–0.5)                                                  |                                                                        |
| Infants (<12 months)                                                       |                                                                        |
| Enoxaparin                                                                 |                                                                        |
| Persantine                                                                  |                                                                        |
| Aspirin                                                                     |                                                                        |
| Children (>12 months)                                                      |                                                                        |
| Warfarin                                                                    | INR 2.7–3.5                                                            |
| Persantine                                                                  | ADP net G 4–8                                                           |
| Aspirin                                                                     | AA inhibition > 70%                                                     |

- ADP net G = \([100% - \text{ADP inhibition}] \times \text{GCKH}] / 100\), CKH = citrated kaolin heparinase.
- AA = arachidonic acid.
Anesthesia with VAD for Non-cardiac surgery

- Establish baseline neurological, renal and hepatic function.
- Temporary conversion from Warfarin or LMWH to Unfractionated heparin allows anticoagulation to be stopped 2 hrs prior to surgery.
- Standard Monitoring with Cerebral oximetry / Aline +/- CVP
- Anti-siphon valves are required on infusions running through central lines if the RV is supported because back pressure may be encountered.
- Antibacterial prophylaxis should be agreed upon in advance.
- Transport: Elevators must be appropriately sized. Battery size?
- Transferring to the OR table must be done with care
- Sterile clear drapes preferred/ alcohol based antiseptic solutions avoided
- Consider Echocardiography
• Fixed rate, variable stroke volume of the VAD makes patients vulnerable to changes in venous and arterial capacitance.
• Hypotension occurs in 70% on induction of anesthesia in patients with a Berlin heart in situ
• Fluid challenges and α-adrenergic agonist (phenylephrine or Norepinephrine)
• Ketamine causes the least disturbance.
• Spontaneous ventilation is preferred to maintain better systemic venous return than IPPV (except in Pulm HT)
• Increased PVR and RV failure need to be treated promptly in the presence of unexplained hypotension (milrinone / nitric oxide/ mild alkalosis)
• Increased SVR risks stasis and thrombosis, so adequate depth of anesthesia is required.
• Monitor the patient, NOT THE VAD
• Flow is Calculated, not measured directly.
• Gravity tubing is acceptable
• Suction alarms
• Battery life is 4-6 hours. (never disconnect from both battery and AC?DC power)
• No chest compressions permitted
• Narrow pulse pressure, so pulse oximetry is useless
• Arrhythmias are better tolerated than other VADS
• Anticoagulate to INR 3
### Decreased Pump Flow Index

<table>
<thead>
<tr>
<th>Differential Diagnosis</th>
<th>Hemodynamic Changes</th>
<th>Echo</th>
<th>HVAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CVP</td>
<td>PAP</td>
<td>PAOP</td>
</tr>
<tr>
<td>Hypovolemia</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Tamponade</td>
<td>↑</td>
<td>↓</td>
<td>Or No Change</td>
</tr>
<tr>
<td>RHF</td>
<td>↑</td>
<td>↑</td>
<td>Or No Change</td>
</tr>
<tr>
<td>Hypertension</td>
<td>←</td>
<td>↑</td>
<td>Or No Change</td>
</tr>
<tr>
<td>Occlusion</td>
<td>↑</td>
<td>↑</td>
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## Increased Pump Flow Index

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</tr>
<tr>
<td>Vasodilation</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
</tr>
<tr>
<td>Aortic Insufficiency</td>
<td>↔</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Thrombus</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

**Echo:**
- Normal
- Normal, Ao opening
- AI, MR, Inc LVEDD
- Dilated LA/LV, Ao Opening, MR

**HVAD:**
- Power: ↑
- Pulsatility: ↑
**Interventions to Consider**

**Hypovolemia**
- Give volume
- Treat bleeding if cause

**Tamponade**
- Surgical takeback

**Right Heart Failure (RHF)**
- Decrease LVAD speed
- Inotropes
- Temporary RVAD

**Hypertension**
- Adjust medications to decrease MAP

**Occlusion**
- Surgical intervention

**Hypervolemia**
- Diuresis
- CRRT

**Vasodilation**
- Eval for cause (e.g., infection, medications)
- Support with fluid, pressors
- Reduce or hold vasodilators

**Aortic Insufficiency**
- Vasodilate
- Reduce speed
- Surgical intervention

**Thrombus**
- Medical management: increasing antiplatelet and anticoagulation medications
- Thrombolytics
- Pump exchange

---

**WARNING:** Serious and life-threatening adverse events, including stroke, have been associated with use of this device. A user must fully consider the risks of this device with that of other treatment modalities before deciding to proceed with device implantation.

In the USA, the HVAD System is intended for use as a bridge to cardiac transplantation in patients who are at risk of death from refractory end-stage left ventricular heart failure.

**CAUTION:** Federal law (USA) restricts this device to sale by or on the order of a physician. Refer to the “Instructions for Use” for complete Indications for Use, Contraindications, Warnings, Precautions, Adverse Events and Instructions prior to using this device. The IFU can be found at www.heartware.com/clinicians/instructions-use.

HEARTWARE, HVAD, MVAD, PAL, and the HEARTWARE logo are trademarks of HeartWare, Inc.
Trouble shooting:

• **Sudden loss of output:**
  
  • Loss of consciousness/ interruption of normal sounds by the pump/ alarm from the driver unit
  
  • Check for Kinks/ leaks / disconnections/ clots

• **Sudden cyanosis:**
  
  • Pulmonary embolism must be considered esp if RVAD in situ or Poor right heart function
  
  • Rt-Lt shunt through a PFO/ASD

• **Arrhythmias:**
  
  • In the event of a malignant dysrhythmia, Cardiac output should be maintained, even if the Right heart is unsupported. (passive pulmonary perfusion may suffice)
  
  • External cardiac compressions must not be performed
  
  • Standard therapy included cardioversion is typical.
Table 6
Proposed management of haemodynamic instability in ventricular assist devices.

<table>
<thead>
<tr>
<th>Haemodynamic change</th>
<th>Possible aetiology</th>
<th>Device Inspection</th>
<th>Possible intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Berlin Heart EXCOR (pulsatile ventricular assist device)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP ↓</td>
<td>Hypovolaemia</td>
<td>Inspect chamber for wrinkling and incomplete filling in diastole</td>
<td>Fluid bolus</td>
</tr>
<tr>
<td></td>
<td>Systemic vasodilation</td>
<td>Chamber may be filling fully</td>
<td>Consider/treat promptly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RV failure or increased PVR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Alpha agonists or vasopressin</td>
</tr>
<tr>
<td>BP ↑</td>
<td>Pain, anxiety, awareness under anesthesia</td>
<td>Inspect chamber for wrinkling during systole</td>
<td>Sedation, analgesia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Avoid increasing systolic driving pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Titrate vasodilators</td>
</tr>
<tr>
<td><strong>HeartMate II left ventricular assist device (axial ventricular assist device)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP ↓</td>
<td>Hypovolaemia</td>
<td>Device flow will decrease and rpm will slow beyond which device will shunt until volume status corrected</td>
<td>Fluid bolus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower dP (aortic-LV pressure) will increase device flow with no change in rpm</td>
<td>Consider/treat RV failure or increased PVR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Alpha agonists or vasopressin</td>
</tr>
<tr>
<td>BP ↑</td>
<td>Pain, anxiety</td>
<td>Decreased device flow without the change in rpm</td>
<td>Sedatives, analgesics</td>
</tr>
<tr>
<td></td>
<td>Awareness under anesthesia</td>
<td></td>
<td>Titrate vasodilators</td>
</tr>
</tbody>
</table>

*LV: left ventricle, RV: right ventricle, PVR: pulmonary vascular resistance, BP: blood pressure.

Thromboelastography (TEG) in conjunction with routine blood test such as lab analysis.
VAD and the single ventricle

- Outcomes with Single ventricles are much worse (42% vs 73% survival)
- VAD has better survival than ecmo in the single ventricle children
- Although Stage 1 patients have dismal outcomes (young and low BSA are negative factors)
- The cause of a failing fontan has to be systemic ventricle failure, seen by an elevated EDP. If it isn’t elevated a VAD will not particularly help
- About ¼ of Berlin hearts inserted were for CHD
- Artificial Hearts
The future:

- **PumpKIN trial**
  - 2002 NHLBI initiates Pediatric Circulatory Support Program
  - Fund the development of 5 durable circulatory assist devices for use in children 2-25 kg
  - 2010 2 axial flow devices, 2 ambulatory compact ECMO systems; RFP for DCCC
  - 2014 Single VAD: Infant Jarvik 2000

- **Trancutaneous Energy Transfer System (TETS)**
  - To avoid transcutaneous power lines
  - Long way off for VADS
  - Potential in Pacemaker/ICD (within a year)