Physiology of Extra-corporeal Life Support

2018 | Foundations of ECLS: Skills, Training and Hands-on Management for New Operators and New Programs

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Financial Disclosures
None
**Education Need/Practice Gap**
ECLS is increasingly being used in adult patients.

Providers need to be aware of the basic physiological concepts of ECLS as well how ECLS works.

**Learning Objectives**
Upon completion of this presentation, attendees will be able to:
• Review the physiology and mechanics of VV and VA ECLS.
• Review the basic anatomy and physiology of ECLS systems

**Expected Outcomes**
The desired change/result in practice is the knowledge of basic physiological concepts as they apply to ECLS.
Why Physiology?

Because ECLS is a life-saving but dangerous tool that should be utilized ONLY by practitioners who understand the physiology of metabolism, oxygen delivery and CO₂ removal.

Normal Physiology
- Systemic oxygen delivery
- CO₂ production and removal

Circuit Design
- Effects native heart & lung

Physiology of ECLS
- Gas exchange capacity

CₐO₂

Pumps
- Non-pulsatile flow

Oxygenators
- Gas transfer
Oxygen Delivery and the Normal Circulation
O₂ Consumption
Consumption = uptake = 120 ml/min/m²
(1/5th of delivered)

Arterial O₂ Content
Determined by Hgb and PO₂
Normal Hgb 15, 100% O₂ sat
O₂ content = 20 ml/dl

O₂ Delivery
Determined by arterial O₂ content
times cardiac output.
DO₂ = (20 ml/dl) X (3 L/min/m²)
= 600 ml/min/m²

Cardiac Output
Normal resting cardiac index is 3 L/min/m²

O₂ Uptake
VO₂ = 120 ml/min/m²

O₂ Delivery > O₂ Consumption
Normal ratio VO₂/DO₂ = 1/5

Venous Return
Contains 80% of delivered O₂
Venous O₂ sat = 80%
Venous O₂ content = 16 ml/dl
AV O₂ cont. difference = 4 ml/dl

O₂ Consumption
Consumption = uptake = 120 ml/min/m²
(1/5th of delivered)
A liquid that contains gas
This 355 ml can of Coke contains 1,775 ml of dissolved CO₂ gas.

CO₂ content of Coke:
(1,775 ml CO₂) ÷ (335 ml Coke) = 5.3 ml/ml

or...
CO₂ Content_{Coke} = 530 ml/100 ml
= 530 ml/deciliter
Blood Oxygen Content

The deciliter (dl)

**Deciliter of Air**

- **Composition of Air**
  - Dry air contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide. We can round off to 80% nitrogen and 20% oxygen.

- **Oxygen Content of Air**
  - One deciliter of air contains 20 ml of oxygen.

**Deciliter of Blood**

- **Unique Ability to Bind Oxygen**
  - Blood exists to transport oxygen.

- **Arterial Blood Oxygen Content**
  - The oxygen content of normal arterial blood is 20 ml/dl.
  - $C_aO_2 = 20$ ml/dl

- **Venous Blood Oxygen Content**
  - The oxygen content of normal venous blood is 16 ml/dl.
  - $C_vO_2 = 16$ ml/dl

Notice that venous blood still contains a lot of oxygen.
Blood Oxygen Content
Measuring the gas content of a liquid

Carbonation Works
CO2 is Highly Soluble in Water
\[ \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 = \text{HCO}_3^- + \text{H}^+ \]

Carbonated Beverages
CO2 Content = 200 to 500 ml/dl

Oxygenation Needs Help
Oxygen is 26X Less Soluble
Dissolved \( \text{O}_2 \): \( C = 0.0031 \text{ ml/dl/mmHg} \)

Plasma
\( \text{O}_2 = 0.3 \text{ ml/dl} \)

Blood
\( \text{O}_2 = 20 \text{ ml/dl} \)

Blood \( \text{O}_2 \) Transport
30 Trillion RBCs
120 days life span
2.4 million per second

Hemoglobin
270 million per RBC

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Oxygen Content and O$_2$ Saturation

Relationship between O$_2$ saturation and content

Normal $\text{DO}_2/\text{VO}_2$ Homeostasis

Oxygen delivery exceeds consumption by 5:1

- **Normal $\text{O}_2$ Delivery**
  - At rest, oxygen delivery exceeds consumption 5X.

- **Increased $\text{O}_2$ Delivery**
  - If oxygen delivery is increased above 5X, consumption remains unchanged. Returning venous blood has increased $\text{O}_2$ content.

- **Reduced $\text{O}_2$ Delivery**
  - If oxygen delivery is reduced, consumption remains unchanged and extraction increases. Returning venous blood has reduced $\text{O}_2$ content.

- **Critically Reduced $\text{O}_2$ Delivery**
  - When oxygen delivery is less than 2X, metabolism becomes delivery-dependent and acidosis occurs.

**DO₂/VO₂ Ratio**

At rest, normal oxygen delivery exceeds consumption by 5:1 (DO₂/VO₂ = 5)

- **O₂ Delivery**: DO₂ (ml/kg/min)
- **O₂ Consumption**: VO₂ (ml/kg/min)

 Venous O₂ saturation mirrors the ratio of oxygen delivery to oxygen consumption.

DO$_2$/VO$_2$ Ratio

Oxygen delivery exceeds consumption by 5:1 (DO$_2$/VO$_2 = 5$)

- **O$_2$ Delivery**: DO$_2$ (ml/kg/min)
- **O$_2$ Consumption**: VO$_2$ (ml/kg/min)

### SvO$_2$
- 86%
- 67%

### Extraction
- **Decreased Extraction (1/7)**: 14% extracted/86% returned
- **Increased Extraction (1/3)**: 33% extracted/67% returned

### SaO$_2$
- 100%

Venous O$_2$ saturation mirrors the ratio of oxygen delivery to oxygen consumption.

O$_2$ Consumption and Delivery in Sepsis

DO$_2$/VO$_2$ relationships are unchanged

Normal conditions. Oxygen delivery exceeds consumption by 5:1 ratio.

Doubling of O$_2$ consumption due to sepsis.

DO$_2$/VO$_2$ predicts venous O$_2$ saturation (SvO2)
Just as at baseline, if arterial blood is fully saturated, venous O$_2$ saturation mirrors the DO$_2$/VO$_2$ ratio.
Intuitive Understanding of ECLS Circuits

Example of V-V ECMO (with recirculation)

- Tubing Length
- Tubing Diameter
- Access Site
- Cannula Position
- Rated Flow
- Max O₂ Delivery
- O₂ Transfer
- Mixing
- Recirculation
- LV Function
- O₂ Delivery
- O₂ Consumption

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Intuitive Understanding of ECLS Circuits

V-V ECMO circuit redesigned to minimize recirculation

When is it necessary?

Dual-lumen RIJ cannula?
Multiple cannulas?
Physiology and Circuit Design

Typical V-A ECMO circuit considerations

- Resistance to flow: tubing length and diameter
- Venous cannula diameter
- Vacuum
- Pressure
- O₂ sat
- Arterial cannula dia.
- + Afterload
- Tissue perfusion
- O₂ Delivery
- O₂ Consumption

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Physiology and Circuit Design

V-A ECMO in severe LV failure: organ perfusion at the expense of cardiac distention

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Thebesian and Bronchial Vessels

Return of systemic venous blood to the left heart causes distention.
Intuitive Understanding or Circuits

V-V ECMO circuit redesigned to minimize recirculation

Oxygenator Failure?

What does it mean when $\text{MVO}_2\text{ sat}$ measured at the oxygenator inlet decreases?

Increased $\text{O}_2$ Consumption (fever, etc.)

Change in LV function?

Change in $\text{O}_2$ delivery?

Why?

Due to anemia?
Gas Exchange in the Lung and Oxygenator Membranes
Gas Exchange in the Lung
Understanding the physiology of extracorporeal support in critical heart and lung disease

Oxygen uptake in the normal lung
Alveolar capillary is 10 \( \mu \) diameter. RBC transit time is one second. Hemoglobin become 100% saturated in .25 seconds.
John Gibbon develops piano-sized roller pump inspired by PE death.
John Gibbon develops piano-sized roller pump inspired by PE death.
Structure of Gas Exchanger

Commercial oxygenator (QUADROX-I Adult)\(^1\)

Hollow fibers (membrane)
Polymer textile produced by spinning (like cotton candy)

Arranged in stacks
Overlapping layers of woven fiber mats

Non-permeable polyurethane heat exchange fibers

Disposable enclosure
With in/out connections for blood, sweep gas, and water

Oxygenator Terminology
Relationship between blood flow $O_2$ delivery

**Rated Flow**
Flow at which the device is able to convert blood\(^1\) from 75% saturation to at least 95% saturation.

**Maximum $O_2$ Delivery**
Running at rated flow, the rate that $O_2$ is added to blood.

\[
= (\text{inlet } O_2 \text{ content}) - (\text{outlet } O_2 \text{ content}) \times \text{flow}
\]

\[
= 6 \text{ ml/dl} \times 7 \text{ l/min}
\]

\[
= 420 \text{ ml/min}
\]

\[\text{Normal resting } O_2 \text{ demand is 120 ml/min/m}^2\]
\[\text{More than adequate for large adults, anemia and hypermetabolic conditions.}\]

1. Blood Hgb 12 gm/dl
Oxygenator Performance

Commercial oxygenator (QUADROX-i Adult)\(^1\)

### Technical Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>QUADROX-i Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended blood flow rating</td>
<td>0.5 – 7 l/min</td>
</tr>
<tr>
<td>Priming volume</td>
<td>215 ml</td>
</tr>
<tr>
<td>Effective gas exchange surface area</td>
<td>1.8 m(^2)</td>
</tr>
<tr>
<td>Effective heat exchange surface area</td>
<td>0.4 m(^2)</td>
</tr>
<tr>
<td>Material of gas exchange fiber</td>
<td>Polypropylene (PP)</td>
</tr>
<tr>
<td>Material of heat exchange fiber</td>
<td>Polyurethane (TPU)</td>
</tr>
</tbody>
</table>

### Performance

#### Pressure Drop

- QUADROX-i Adult with integrated arterial filter
- QUADROX-i Adult

Low pressure drop on the blood side

![Pressure Drop Graph](Image)

#### Carbon Dioxide Transfer

- Gas/blood flow ratio
  - 2:1
  - 1:1
  - 0.5:1

Optimized carbon dioxide elimination at any gas/blood flow ratio

![Carbon Dioxide Transfer Graph](Image)

#### Heat Exchange Performance

- QUADROX-i Adult and QUADROX-i Adult with integrated arterial filter

Efficient heat exchange – a feature of all QUADROX-i oxygenators

![Heat Exchange Graph](Image)

#### Oxygen Transfer

- QUADROX-i Adult and QUADROX-i Adult with integrated arterial filter

Good transfer rates with high and low blood flow

![Oxygen Transfer Graph](Image)

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Oxygenator Problems
What can go wrong?

**Purpose**
Add $O_2$ and remove $CO_2$
No mixing of blood with gas or coolant

**Materials**
Originally silicone rubber; now microporous polypropylene, polymethylpentene (PMP). PVC, polyurethane.
The Balance of Bleeding and Clotting During ECLS
Causes of Bleeding on ECMO

Bleeding is the leading causes of morbidity and mortality on ECMO\(^1,2\)

1. Thrombocytopenia
   Common on ECMO and associated with increased bleeding and mortality [72–74]. Surface activation and consumption.

2. Hyperfibrinolysis
   Thrombus deposition on circuit components triggers excessive fibrinolysis. Pathological bleeding with very high D-dimer levels [83, 84].

3. Disseminated Intravascular Coagulation (DIC)
   Contact activation on membrane consumes platelets and coagulation factors. Simultaneous bleeding and thrombosis [77, 78].

4. Acquired von Willebrand Syndrome
   Mediated by shear. Seen in up to 94% patients on ECMO [101]. Managed by reducing pump speed and upsizing cannulas to reduce turbulence.

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3. Wo Y, Brisbois EJ, Bartlett RH, Meyerhoff ME. Recent advances in thromboresistant and antimicrobial polymers for biomedical applications... Biomater Sci. 2016 Aug 19;4(8):1161-83.
Acquired von Willebrand Syndrome

Bleeding is the leading causes of morbidity and mortality for patients on ECMO\(^1,2\)

**Etiology**
Shear stress. Seen with aortic stenosis, and extracorporeal circulations (axial flow LVADs and ECMO)\(^1,3\)

**Prevalence**
Common. One study reported acquired von Willebrand syndrome in up to 94% of patients on ECMO\(^4\)

**Diagnosis**
No single diagnostic test. Special assays demonstrate loss of high molecular weight multimers in patients on ECMO.\(^5\)

**Management**
Reduce pump speed and increase cannula size to minimize turbulent flow, or wean and de-cannulate.

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Bleeding versus Clotting

Bleeding and thrombosis are the leading causes of morbidity and mortality on ECMO\textsuperscript{1-5}

Consumptive Coagulopathy
Patients presenting with hypotension or circulatory arrest have very poor outcomes with a 90-day mortality rate of 52%.\textsuperscript{1}

Surface Activation
Patients presenting with hypotension or circulatory arrest have very poor outcomes with a 90-day mortality rate of 52%.\textsuperscript{1}
### Thrombotic Complications: Adult ECMO

For respiratory and cardiac support, adapted from ELSO International Summary Report, January 2016.

<table>
<thead>
<tr>
<th>Complication</th>
<th>Reported (%)</th>
<th>Survival (%)</th>
<th>Reported (%)</th>
<th>Survival (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical clots: oxygenator</td>
<td>13.8</td>
<td>57</td>
<td>9.2</td>
<td>42</td>
</tr>
<tr>
<td>Mechanical: clots: bridge</td>
<td>1.1</td>
<td>58</td>
<td>0.6</td>
<td>56</td>
</tr>
<tr>
<td>Mechanical: clots: bladder</td>
<td>1.0</td>
<td>57</td>
<td>0.2</td>
<td>47</td>
</tr>
<tr>
<td>Mechanical: clots: hemofilter</td>
<td>2.3</td>
<td>48</td>
<td>1.3</td>
<td>25</td>
</tr>
<tr>
<td>Mechanical: clots: other</td>
<td>5.9</td>
<td>57</td>
<td>6.2</td>
<td>41</td>
</tr>
<tr>
<td><strong>Total thrombotic</strong></td>
<td><strong>24.1</strong></td>
<td><strong>57</strong></td>
<td><strong>17.5</strong></td>
<td></td>
</tr>
</tbody>
</table>

## Bleeding Complications: Adult ECMO

For respiratory and cardiac support, adapted from ELSO International Summary Report, January 2016

<table>
<thead>
<tr>
<th>Complication</th>
<th>Respiratory (Reported %)</th>
<th>Respiratory (Survival %)</th>
<th>Cardiac (Reported %)</th>
<th>Cardiac (Survival %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI Bleeding</td>
<td>6.0</td>
<td>39</td>
<td>4.3</td>
<td>25</td>
</tr>
<tr>
<td>Cannulation Site Bleeding</td>
<td>13.8</td>
<td>52</td>
<td>18.6</td>
<td>39</td>
</tr>
<tr>
<td>Surgical Site Bleeding</td>
<td>11.1</td>
<td>46</td>
<td>20.5</td>
<td>34</td>
</tr>
<tr>
<td>Hemolysis (PfHb &gt;50)</td>
<td>5.7</td>
<td>46</td>
<td>5.7</td>
<td>32</td>
</tr>
<tr>
<td>Hemorrhagic: DIC</td>
<td>3.2</td>
<td>27</td>
<td>3.6</td>
<td>22</td>
</tr>
<tr>
<td><strong>Total Bleeding Complications</strong></td>
<td><strong>39.8</strong></td>
<td><strong>52.7</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A/C Monitoring on ECMO: Best Practice

For respiratory and cardiac support, adapted from ELSO International Summary Report, January 2016

Unfractionated heparin

Achieve therapeutic

ACT goal based on anti-Xa

Anti-Xa 0.3 to 0.7

ACT Target

ACT Hourly

ACT drift re-calibrated to anti-Xa

Anti-Xa 0.3 to 0.7
Physiology Considerations for Pumps and Tubing
Pressure-Flow Relationships

Determinants of flow in ECMO circuit

Resistance ($R$) = \frac{8 \eta L}{\pi r^4}

Flow ($F$) = \frac{P_1 - P_2}{R} = \frac{(\Delta P) \cdot \pi r^4}{8 \eta L}

Variables under our control in an ECMO circuit:
1) Pump pressure; 2) tubing/cannula length; and 3) Tubing/cannula diameter. Adult ECMO circuits almost always use 3/8” tubing. Therefore, adequate cannula size is the most important determinant of flow.

Small changes in cannula diameter (or radius) yield large changes in flow.
Cannulas and Tubing

Basic principles

- Flow is most likely to be limited by diameter of the venous cannula
  - Femoral cannulas are limited by length
  - Right IJ to SVC gives shortest length and largest diameter (not always feasible or desirable).
- Keep tubing as short as reasonably possible for transport, etc.
- Match artery and venous cannulas
Cannula Pressure-Flow Curves

Performance of commonly-used femoral arterial and venous cannulas

**Edwards Fem-Flex II Femoral Arterial Cannula Pressure Drop vs. Flow**

**Edwards QuickDraw Femoral Venous Cannula Pressure Drop vs. Flow**
Non-Pulsatile Flow

Physiology of pulsatile versus non-pulsatile flow during ECLS
Physiology of Brain and Limb Perfusion on ECLS
Access Site Complications

Limb ischemia is one of the most feared and potentially irreversible complications of VA ECLS


- **Ischemia**: 12.5 to 22.6% (Pooled 16.9%)
- **Fasciotomy or compartment**: 7.3 to 14.5% (Pooled 10.3%)
- **Amputation**: 2.3 to 9.3% (Pooled 4.7%)
Mechanisms of **Limb Ischemia**

Multiple reasons for limb ischemia in patients on VA ECMO

1. **Physical obstruction by cannula**
   Cannulae capable of adequate circulatory support (18-20 F) may partially or totally obstruct iliac and femoral arteries.

2. **Pre-existing atherosclerosis**
   Underlying disease is common in patients who require VA ECMO. Non-occlusive lesions become totally occlusive with cannula insertion.

3. **Vasospasm due to catecholamines**
   High-dose vasopressors can cause marked vasospasm and severe distal ischemia in normal extremities. Vasospasm contributes to cannula obstruction.

4. **Non-pulsatile flow**
   Severe PAD has low amplitude, monophasic flow at baseline. Non-pulsatile flow on pump removes systolic driving force in stenotic or collateral-dependent vessels.

5. **Hypotension**
   Hypotension impairs perfusion of cannulated and non-cannulated limb, exacerbating all other mechanisms of ischemia.

6. **Cannulation injury**
   Aggressive cannulation technique can cause vasospasm, dissection, compressive hematoma, and avulsed plaque and thrombosis.
Occlusive Vascular Disease in ECLS

Chronic occlusion of abdominal aorta and iliac arteries
Ischemia Affects Mainly the Distal Leg

Collateral circulation around the hip joint preserves upper leg in VA ECLS

COLLATERAL CIRCULATION
ARteries of the Hip

- Medial femoral circumflex
- Lateral femoral circumflex
- Obturator artery
- Superior gluteal
- Inferior gluteal

Collateral anastomoses around the hip—why ischemia on ECLS spares the upper leg
Complications of VA ECMO for Cardiogenic Shock and Arrest

Limb Ischemia and bleeding
In meta-analysis, limb ischemia (including compartment syndrome, gangrene, toe necrosis, neuropathy, fasciotomy and amputation) is very common, occurring in about one fourth of patients on VA ECMO.1

Major Bleeding
Bleeding, primarily related to access site, occurs in nearly half of VA ECMO patients.

Infection
Many access site-related infections can be avoided through careful percutaneous cannulation techniques.

Access for cannulation and distal perfusion

Lower Extremity Artery Size

Common femoral should accept 15-20 F cannula. SFA should accept 8 F cannula or sheath. PT should accept 6-8 F sheath. DP is the smallest accessible artery at 2-2 mm diameter, and should accept 6 F sheath.
Perfusion requirements of the normal cannulated leg at rest.\textsuperscript{1}

Independent of age, weight, height, muscle mass.\textsuperscript{1}

- **Common Femoral**: $284 \pm 21$ mL/min
- **SFA**: $152 \pm 10$ mL/min
- **Popliteal**: $72 \pm 5$ mL/min
- **DP**: $3 \pm 1$ mL/min
Distal Perfusion Sheath

Various devices have been described: sheaths, cannulae, central venous catheters, etc.

Limb Ischemia and bleeding
In meta-analysis, limb ischemia (including compartment syndrome, gangrene, toe necrosis, neuropathy, fasciotomy and amputation) is very common, occurring in about one fourth of patients on VA ECMO.

Major Bleeding
Bleeding, primarily related to access site, occurs in nearly half of VA ECMO patients.
Distal Perfusion Cannulae

Availability, size and flow performance characteristics of small arterial cannulae

Edwards Fem-Flex II Pediatric Arterial Cannulae with Introducers

<table>
<thead>
<tr>
<th>Model No</th>
<th>French Size</th>
<th>Tip Length</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMII008A</td>
<td>8 F (2.7 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII010A</td>
<td>10 F (3.3 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII012A</td>
<td>12 F (4.0 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII014A</td>
<td>14 F (4.7 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII008AT</td>
<td>8 F (2.7 mm)</td>
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<td>6.5 cm</td>
<td>¼ Vented</td>
</tr>
</tbody>
</table>

Tip length may be too short for adult femoral insertion

Prophylactic DPC and Limb Ischemia

Literature indicates


28%

Overall rate of major limb ischemia requiring fasciotomy or amputation
Limb Ischemia Monitoring the “Six Ps”

Patients on femoral VA ECMO require regular monitoring of the physical exam for limb ischemia.

Physical findings are subjective and unreliable

1. Pulselessness
   - Absent on continuous flow ECMO despite good perfusion
   - Unreliable

2. Pallor
   - Anemia, vasoconstriction.
   - Subjective

3. Pain
   - Absent in sedated patient
   - Unreliable

4. Poikilothermia
   - Control limb cold in shock
   - Subjective

5. Paresthesia
   - Absent in sedated patient
   - Unreliable

6. Paralysis
   - Late, masked by sedation
   - Delayed

Includes capillary refill time <5 seconds, Doppler signal strength, and calf muscle rigidity (a late finding).

Unlike direct, continuous measures of perfusion:
- ✓ Regional oximetry
- ✓ Perfusion line pressure
- ✓ Perfusion line flow

Components of Regional Oximetry System

Near-infrared spectroscopy (NIRS) to continuously monitor regional tissue oxygen saturation (rSO₂)

Deep tissue regional oxygenation is calculated by subtracting the effects of shallow tissue from those of deep tissue by manipulating the signals received by the two detectors on each sensor.
Avoiding Limb Ischemia

Should we utilize continuous, noninvasive regional tissue oximetry ($rSO_2$) routinely?

Conventional methods inadequate. Skin color, temperature, capillary refill are subjective.

Doppler unreliable. Perfusion may be adequate despite non-pulsatile flow on ECLS.

Vague safe limits. Subjective assessment leads to ischemic complications (fasciotomy, amputation).

Non-invasive tissue oximetry. Early detection and correction of ischemic complications. Figure shows correction of ischemia. Reduced plateau may indicate microvascular injury.

Avoiding Limb Ischemia

Should we utilize continuous, noninvasive regional tissue oximetry ($rSO_2$) routinely?

**Figure** shows early detection and correction of limb ischemia due to thrombosis of perfusion cannula.

**Non-invasive tissue oximetry.**

**Standard of care?** Probably yes, pending further study of efficacy.

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Conclusion: Audience Response Question
1. Which of the following statements regarding the physiology of ECLS is FALSE?

A) Under normal conditions, O₂ uptake exactly matches O₂ consumption. You can measure either value and get the same results.

B) Under normal conditions, O₂ delivery exactly matches O₂ consumption.

C) When the arterial blood is 100% saturated, the mixed venous O₂ saturation exactly reflects the ratio of oxygen delivery to oxygen consumption.

D) Normally, the circulation delivers 5 times more oxygen than the body tissues require. As a result, venous blood still has a high oxygen content at 80% of arterial blood.

E) All of these statements are TRUE.
Statement B is FALSE. Oxygen delivery does not match consumption. In fact, \( O_2 \) delivery is 5X greater than \( O_2 \) consumption. This 5:1 ratio indicates normal physiology. When the \( DO_2/VO_2 \) ratio falls below 2, things are very abnormal—tissue oxygenation becomes flow-dependent and acidosis begins.

Oxygen uptake always equals oxygen consumption. You can measure either value and get the same results.

When the arterial blood is 100% saturated, the mixed venous \( O_2 \) saturation reflects the ratio of oxygen delivery to oxygen consumption. The mixed venous \( O_2 \) saturation indicates the \( DO_2/VO_2 \) ratio. Normally, the ratio is 5, indicating that the circulation is delivering 5 times more oxygen than the body tissues require.

Normal venous blood contains a lot of oxygen content. Normal arterial blood with Hgb 15 and 100% \( O_2 \) saturation has an \( O_2 \) content of 20 ml/dl. Venous blood has an \( O_2 \) content of 16 ml/dl, which is 80% of the arterial \( O_2 \) content.
2. Which of the following statements regarding the physiology of ECLS is TRUE?

A) Limb ischemia (including compartment syndrome, fasciotomy and amputation) is a rare but serious complication of V-A ECMO.

B) Limb ischemia can be avoided by frequent, careful physical examinations.

C) Distal perfusion catheters should be used only for well documented limb ischemia. Since most limbs do not develop ischemia, prophylactic DPCs are not appropriate. Evidence shows that risk of bleeding usually outweighs the potential benefit of prophylactic DPCs.

D) Regional tissue oximetry can detect early cerebral and limb ischemia.
Answer:

The only true answer is D. Regional tissue oximetry is able to detect cerebral and limb ischemia at a time when intervention is likely to help.

Sadly, Limb ischemia, fasciotomy and amputation are common complications of V-A ECMO, affecting 17%, 10% and 5% of patients, respectively. The physical examinations for limb ischemia is notoriously subjective and unreliable.

There is good evidence that prophylactic distal perfusion catheters are very effective for avoiding limb ischemia. While there is still some debate, prophylactic DPCs should probably be the standard of care for all V-A ECMO patients. Regional tissue oximetry can detect early cerebral and limb ischemia. While there is still some debate, noninvasive regional tissue oximetry (rSO$_2$) is likely to become standard-of-care.
Thank you for listening!
Distal Perfusion Cannulae

Availability, size and flow performance characteristics of small arterial cannulae

Bio-Medicus NextGen Pediatric Arterial Cannulae with Introducers

For percutaneous insertion over a .025 inch guidewire

<table>
<thead>
<tr>
<th>Model No</th>
<th>French Size</th>
<th>Tip Length</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>96820-108</td>
<td>8 F (2.7 mm)</td>
<td>10.0 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>96820-110</td>
<td>10 F (3.3 mm)</td>
<td>10.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>96820-112</td>
<td>12 F (4.0 mm)</td>
<td>11.0 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>96820-114</td>
<td>14 F (4.7 mm)</td>
<td>11.5 cm</td>
<td>¼ Non-vented</td>
</tr>
</tbody>
</table>

With ¼ inch non-vented connector.

The 8F cannula appears to be more than adequate to meet resting perfusion needs of the normal lower extremity (approximately 0.3 L/min).
Distal Perfusion Cannulae
Availability, size and flow performance characteristics of small arterial cannulae

Edwards Fem-Flex II Pediatric Venous Cannulae
With dilator for percutaneous insertion guidewire

<table>
<thead>
<tr>
<th>Model No</th>
<th>French Size</th>
<th>Tip Length</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMII008V</td>
<td>8 F (2.7 mm)</td>
<td>11.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII010V</td>
<td>10 F (3.3 mm)</td>
<td>11.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII012V</td>
<td>12 F (4.0 mm)</td>
<td>11.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII014V</td>
<td>14 F (4.7 mm)</td>
<td>11.5 cm</td>
<td>¼ Non-vented</td>
</tr>
</tbody>
</table>

Longer tip and similar flow performance compared to Edwards pediatric arterial cannulae

Edwards Fem-Flex II Venous Cannulae
Flow Performance (Pressure Drop vs. Arterial Line Flow)

![Flow Performance Graph](https://example.com/flow-performance-graph.png)

# Distal Perfusion Cannulae

Availability, size and flow performance characteristics of small arterial cannulae

## Edwards Fem-Flex II Pediatric Arterial Cannulae with Introducers

<table>
<thead>
<tr>
<th>Model No</th>
<th>French Size</th>
<th>Tip Length</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMII008A</td>
<td>8 F (2.7 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII010A</td>
<td>10 F (3.3 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII012A</td>
<td>12 F (4.0 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII014A</td>
<td>14 F (4.7 mm)</td>
<td>6.5 cm</td>
<td>¼ Non-vented</td>
</tr>
<tr>
<td>FEMII008AT</td>
<td>8 F (2.7 mm)</td>
<td>6.5 cm</td>
<td>¾ Vented</td>
</tr>
<tr>
<td>FEMII010AT</td>
<td>10 F (3.3 mm)</td>
<td>6.5 cm</td>
<td>¾ Vented</td>
</tr>
<tr>
<td>FEMII012AT</td>
<td>12 F (4.0 mm)</td>
<td>6.5 cm</td>
<td>¾ Vented</td>
</tr>
<tr>
<td>FEMII014AT</td>
<td>14 F (4.7 mm)</td>
<td>6.5 cm</td>
<td>¾ Vented</td>
</tr>
</tbody>
</table>

Tip length may be too short for adult femoral insertion

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### Edwards Fem-Flex II Pediatric Cannulae

Flow Performance (Pressure Drop vs. Arterial Line Flow)

- **8 Fr.**
- **10 Fr.**
- **12 Fr.**
- **14 Fr.**

![Graph showing flow rate vs. pressure drop with model numbers and French sizes](image)

- **0.3**

---

**Flow Rate (L/min), H2O at Room Temperature**

**Pressure Drop (mmHg)**
Bleeding on ECMO
### Other Complications: Adult ECMO

For respiratory and cardiac support, adapted from ELSO International Summary Report, January 2016

<table>
<thead>
<tr>
<th>Complication</th>
<th>Respiratory</th>
<th>Cardiac</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reported (%)</td>
<td>Survival (%)</td>
</tr>
<tr>
<td>Neuro: Stroke</td>
<td>2.0</td>
<td>30</td>
</tr>
<tr>
<td>Neuro: CNS hemorrhage</td>
<td>3.8</td>
<td>21</td>
</tr>
<tr>
<td>Cardiac Tamponade</td>
<td>1.7</td>
<td>49</td>
</tr>
<tr>
<td>Pulmonary hemorrhage</td>
<td>6.3</td>
<td>39</td>
</tr>
<tr>
<td>Limb Ischemia</td>
<td>0.9</td>
<td>35</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>14.7</strong></td>
<td><strong>35</strong></td>
</tr>
</tbody>
</table>

Anticoagulation Monitoring on ECMO

ELSO 2014 Guidelines recommend ECLS center develop their own approach


Activated Clotting Time (ACT)
- Rapid, inexpensive, point-of-care
- Used by 97% of ECMO programs
- Poor standardization among ACT devices
- Affected by many variables including anemia, platelet abnormalities, fibrinogen levels, hypothermia, etc.
- Poor correlation with anti-Xa activity ($r = .14)^2$

Partial Thromboplastin Time (aPTT)
- Widely available
- Inexpensive
- Long turn-around time
- Poor standardization of methods
- Affected by many biological variables
- Poor correlation with other measures

Anti-Xa Activity
- Direct measurement of heparin activity
- Increased time in therapeutic range
- Less bleeding, fewer transfusions
- Improved survival in ECLS patients
- Lack of standardization between reagents
- Delayed turn-around time

Viscoelastic Tests (TEG, ROTEM)
- Thromboelastography (TEG) and Rotational thromboelastometry (ROTEM)
- Global assessment of hemostasis
- Can be point-of-care
- Lack of standardization among instruments
- Limited data on association with clinical outcomes

Lack of standardization between reagents
5:1 Ratio

The relationship between oxygen delivery and consumption (DO₂/VO₂)

Oxygen Delivery Under Resting Conditions

a) Normal O₂ Delivery
   At rest, oxygen delivery exceeds consumption 5X.

b) Increased O₂ Delivery
   If oxygen delivery is increased above 5X, consumption remains unchanged. Returning venous blood has increased O₂ content.

c) Reduced O₂ Delivery
   If oxygen delivery is reduced, consumption remains unchanged and extraction increases. Returning venous blood has reduced O₂ content.

d) Critically Reduced O₂ Delivery
   When oxygen delivery is less than 2X, metabolism becomes delivery-dependent.
5:1 Ratio

The relationship between oxygen delivery and consumption (DO₂/VO₂)

O₂ Delivery: DO₂ (ml/kg/min)

O₂ Consumption: VO₂ (ml/kg/min)
**DO₂/VO₂ Ratio**

Oxygen delivery exceeds consumption by 5:1 (DO₂/VO₂ = 5)

- **O₂ Delivery:** DO₂ (ml/kg/min)
- **O₂ Consumption:** VO₂ (ml/kg/min)

**SvO₂:**
- 86%
- 67%

**Decreased Extraction (1/7):**
- 14% extracted/86% returned

**Increased Extraction (1/3):**
- 33% extracted/67% returned

**SaO₂:**
- 100%

Venous O₂ saturation mirrors the ratio of oxygen delivery to oxygen consumption.
Some Recirculation
Understanding physiology
Some Recirculation
Understanding Physiology
O₂ Consumption and Delivery in Sepsis

DO₂/VO₂ relationships are unchanged

Normal conditions. Oxygen delivery exceeds consumption by 5:1 ratio.

Doubling of O₂ consumption due to sepsis.

DO₂/VO₂ predicts venous O₂ saturation (SvO₂)
Just as at baseline, if arterial blood is fully saturated, venous O₂ saturation mirrors the DO₂/VO₂ ratio.
5:1 Ratio
The relationship between oxygen delivery and consumption (DO$_2$/VO$_2$)

O$_2$ Delivery: DO$_2$ (ml/kg/min)
O$_2$ Consumption: VO$_2$ (ml/kg/min)

Oxygen Delivery Under Resting Conditions

a) Normal O$_2$ Delivery
At rest, oxygen delivery exceeds consumption 5X.

b) Increased O$_2$ Delivery
If oxygen delivery is increased above 5X, consumption remains unchanged. Returning venous blood has increased O$_2$ content.

c) Reduced O$_2$ Delivery
If oxygen delivery is reduced, consumption remains unchanged and extraction increases. Returning venous blood has reduced O$_2$ content.

d) Critically Reduced O$_2$ Delivery
When oxygen delivery is less than 2X, metabolism becomes delivery-dependent.