ECMO Circuit Flow Impacts on General Oxygen Delivery, Synchronizing with Patient’s Needs

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Disclosure

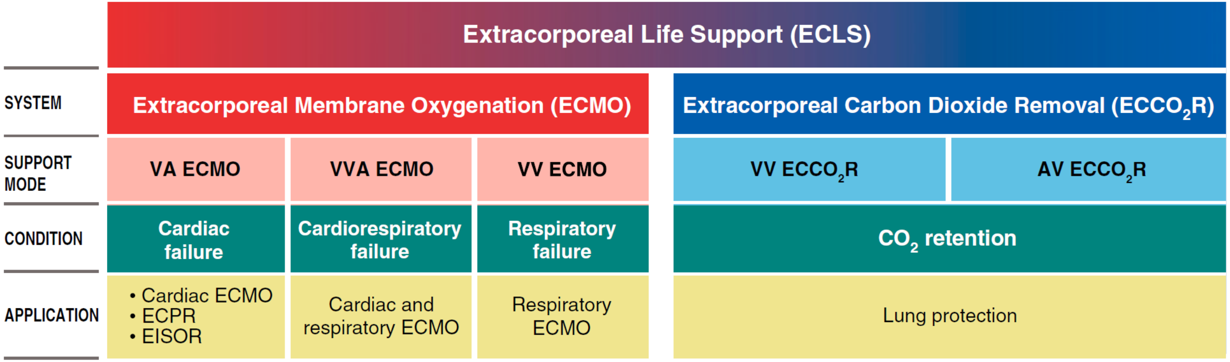
I have no conflict of interests to disclose

Terminology

- Veno-venous / Veno-arterial extracorporeal membrane oxygenation (**VV or VA ECMO**)
- Oxygen content (**CO_2**)
- Oxygen delivery (**DO_2**)
- Oxygen consumption (**VO_2**)
- Oxygen extraction (**VO_2**)
- Cardiac output (**CO**)
- Left ventricular outflow tract (**LVOT**)

ExtraCorporeal Life Support (ECLS)

- Mechanical devices to support heart and/or lung functions;
- A different approach to treating patients with ECLS;
- Require additional understanding of cardiopulmonary physiology, pathophysiology;
- Basic principles and physiology of the ECLS device itself



	Extracorporeal Life Support (ECLS)				
SYSTEM	**Extracorporeal Membrane Oxygenation (ECMO)**			**Extracorporeal Carbon Dioxide Removal (ECCO$_2$R)**	
SUPPORT MODE	**VA ECMO**	**VVA ECMO**	**VV ECMO**	**VV ECCO$_2$R**	**AV ECCO$_2$R**
CONDITION	**Cardiac failure**	**Cardiorespiratory failure**	**Respiratory failure**	**CO$_2$ retention**	
APPLICATION	• Cardiac ECMO • ECPR • EISOR	Cardiac and respiratory ECMO	Respiratory ECMO	Lung protection	

Conrad, S.A. *et al.* (2018) “The Extracorporeal Life Support Organization Maastricht Treaty for Nomenclature in Extracorporeal Life Support A Position Paper of the Extracorporeal Life Support Organization,” *American journal of respiratory and critical care medicine*, 198(4), pp. 447–451.

Patient's Needs / Cardiopulmonary Physiology

- **Normal metabolism** – amount of oxygen consumed per minute (**VO_2**)
  - **VO_2 = 3 ml/kg/min;**
  - Amount of oxygen for metabolism is normally five times the amount used by the tissues (DO_2 / VO_2 = 5:1);
  - **$VO_2 = CO \times (CaO_2 – CvO_2)$**
- Oxygen content (**CO_2**) = **(1.34 x Hb x Saturation) + ($P0_2$ x 0.003)**
  - Normally (a) 20 mlO_2/dL / *for C(v)O2 15 mlO_2/dL*
- Oxygen delivery **(DO_2) = CO x CaO_2**
  - CO (Cardiac output) measured by thermodilution or Echo: CO = HR x SV / SV = LVOT area x LVOT VTI;
  - **Normally 1000 mlO_2/min**

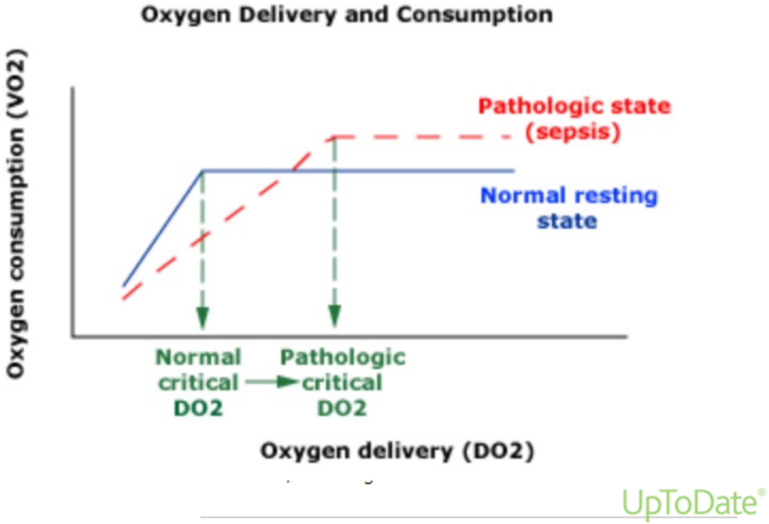
Patient’s Needs / Cardiopulmonary Physiology

- DO_2 and VO_2 ratio = maintaining 5:1*

**At rest 20% of oxygen used for metabolism, 80% - leaving in the venous blood*

- Normally for patient <u>breathing air</u>
  - Arterial: PaO2 – 90 mmHg / saturation – 100% / Ca02 – 20 mlO_2/dL
  - Venous: PvO2 – 40 mmHg / saturation – 80% / Ca02 – 15 mlO_2/dL

Oxygen delivery (DO2) and consumption (VO2)



Cardiopulmonary Pathophysiology and ECMO

- **Affected DO_2 and VO_2 ratio**
  - Low CO, anaemia, hypoxemia → critically low DO2 (<2:1) → aerobic metabolism switches to anaerobic→ lactate acidosis

- **ECMO**
  - Cannulation strategy: size, depth/position, risk of recirculation
  - Pumps: pressure
  - Membrane lungs: inlet/outlet 0_2; 100% O_2; size; flow rate; blood flow:gas flow = 1:1; remove of CO2;
  - ECMO Blood Flow was the Main Determinant of Arterial Oxygenation
  - Blood flow – limitations (4-5 /min) / 60-80 ml/kg/min (dry weight) and >60% of CO
  - VA ECMO – risk of Harlequin syndrome

VV ECMO – No Functional Lung

- In Severe ARDS with VV-ECMO, the Lungs Contribute Little or Nothing to Gas Exchange
- Right atrium (RA): oxygenated blood from ECMO + venous blood from sistemic organs

  - Arterial saturation ranges from 60 to 90 % *(depending on ECMO flow, native venous flow, lung function and cardiac output)*
  - **NORMAL SYSTEMATIC OXYGEN DELIVERY** (if CO and Hbg conc. adequate)
  - Hypoxemia (PaO2 40-60 mmHg, SaO2 70-90%) always occurs with VV support and is adequate to maintain normal oxygen delivery

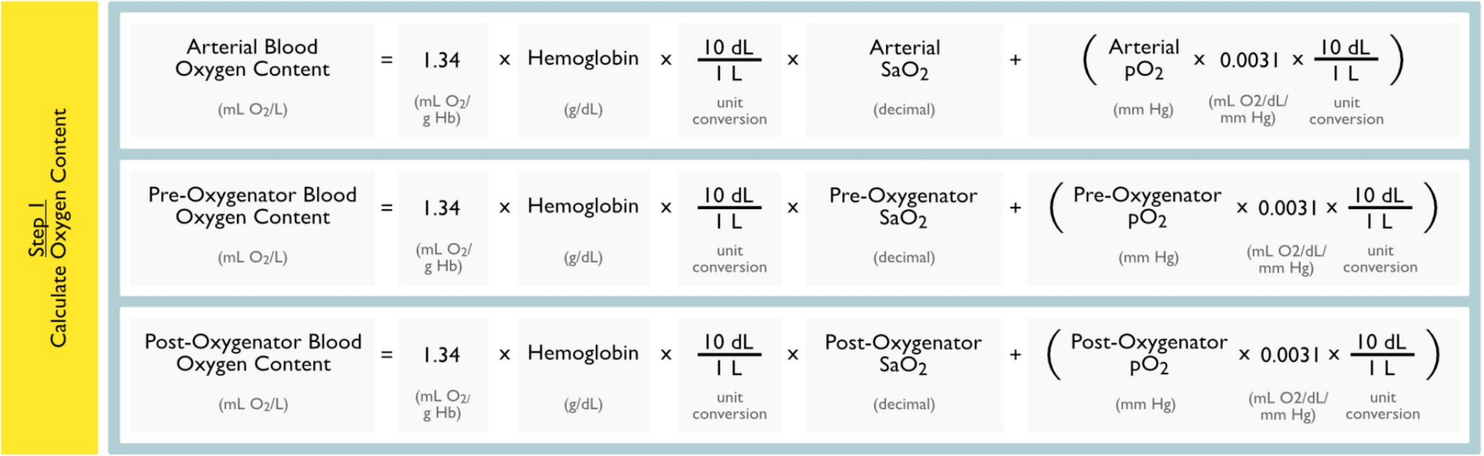
- CO = ECMO flow + Native venous flow

Date for DO_2/VO_2 Consuption Ratio

- **Patient monitoring**
  - Ventilation parameters
  - Hemodynamic
  - Arterial and venous blood gases analyse
  - Haemoglobin/ haematocrit levels
  - Cardiac function

- **ECMO system monitoring**
  - Flow
  - Pressures
  - Inlet-outlet oxygen content

Calculation of DO2/VO2 Ratio During ECMO



Step 1

Calculate Oxygen Content

$$\underset{(\text{mL } O_2/\text{L})}{\text{Arterial Blood Oxygen Content}} = \underset{(\text{mL } O_2/\text{g Hb})}{1.34} \times \underset{(\text{g/dL})}{\text{Hemoglobin}} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \times \underset{(\text{decimal})}{\text{Arterial } SaO_2} + \left(\underset{(\text{mm Hg})}{\text{Arterial } pO_2} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \right)$$

$$\underset{(\text{mL } O_2/\text{L})}{\text{Pre-Oxygenator Blood Oxygen Content}} = \underset{(\text{mL } O_2/\text{g Hb})}{1.34} \times \underset{(\text{g/dL})}{\text{Hemoglobin}} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \times \underset{(\text{decimal})}{\text{Pre-Oxygenator } SaO_2} + \left(\underset{(\text{mm Hg})}{\text{Pre-Oxygenator } pO_2} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \right)$$

$$\underset{(\text{mL } O_2/\text{L})}{\text{Post-Oxygenator Blood Oxygen Content}} = \underset{(\text{mL } O_2/\text{g Hb})}{1.34} \times \underset{(\text{g/dL})}{\text{Hemoglobin}} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \times \underset{(\text{decimal})}{\text{Post-Oxygenator } SaO_2} + \left(\underset{(\text{mm Hg})}{\text{Post-Oxygenator } pO_2} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10\text{ dL}}{1\text{ L}}} \right)$$

- Constant 13.4 mL O2/g Hb: accounts for the fact that 1.34 ml of O2 is carried per g of Hb (13.4 is used in the equation to correct the units from dL to L)
- Constant 0.0031 mL O2/L/mm Hg: solubility coefficient of oxygen at body temperature

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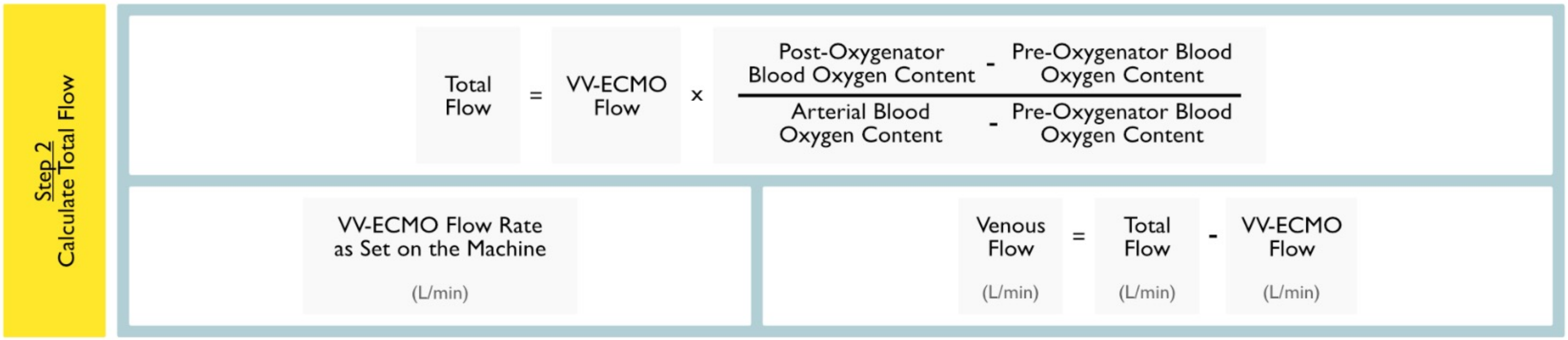
Calculation of DO2/VO2 Ratio During ECMO



Step 2
Calculate Total Flow

$$\text{Total Flow} = \text{VV-ECMO Flow} \times \frac{\text{Post-Oxygenator Blood Oxygen Content} - \text{Pre-Oxygenator Blood Oxygen Content}}{\text{Arterial Blood Oxygen Content} - \text{Pre-Oxygenator Blood Oxygen Content}}$$

VV-ECMO Flow Rate as Set on the Machine (L/min)

Venous Flow (L/min) = Total Flow (L/min) - VV-ECMO Flow (L/min)

- When Two Blood Flows Containing Different Oxygen Contents Mix, the Resultant Oxygen Content is the Average of the Amount of Oxygen Content in Each of the Two Flows
- **Total oxygen compsuption**: *[(Post-Oxygenator Oxygen Content x VV-ECMO Flow)/Total Flow] + [(Pre-Oxygenator Oxygen Content x Native Venous Flow)/Total Flow]*

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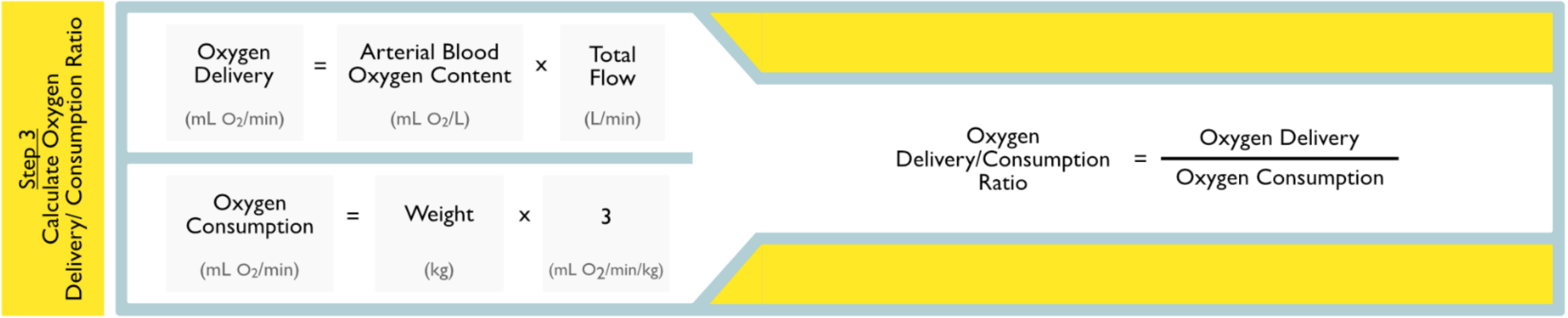
Calculation of DO2/VO2 Ratio During ECMO



Step 3
Calculate Oxygen Delivery/ Consumption Ratio

Oxygen Delivery (mL O_2/min) = Arterial Blood Oxygen Content (mL O_2/L) x Total Flow (L/min)

Oxygen Consumption (mL O_2/min) = Weight (kg) x 3 (mL O_2/min/kg)

$$\text{Oxygen Delivery/Consumption Ratio} = \frac{\text{Oxygen Delivery}}{\text{Oxygen Consumption}}$$

- Oxygen Consumption = Weight (in kg) x 3 mL O2/kg/min

Maintain Oxygen Delivery/Oxygen Consumption Ratio >3

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Sample Calculation of Oxygen Delivery (DO_2)/Oxygen Consumption (VO_2) Ratio During Venovenous Extracorporeal Membrane Oxygenation (VV-ECMO)

Step 1 Calculate Oxygen Content

$$\underset{(\text{mL } O_2\text{/L})}{\text{Arterial Blood Oxygen Content}} = \underset{(\text{mL } O_2\text{/g Hb})}{1.34} \times \underset{(\text{g/dL})}{10.5} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \times \underset{(\text{decimal})}{0.88} + \left(\underset{(\text{mm Hg})}{50} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \right) = \underset{(\text{mL } O_2\text{/L})}{125.4}$$

$$\underset{(\text{mL } O_2\text{/L})}{\text{Pre-Oxygenator Blood Oxygen Content}} = \underset{(\text{mL } O_2\text{/g Hb})}{1.34} \times \underset{(\text{g/dL})}{10.5} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \times \underset{(\text{decimal})}{0.64} + \left(\underset{(\text{mm Hg})}{40} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \right) = \underset{(\text{mL } O_2\text{/L})}{91.3}$$

$$\underset{(\text{mL } O_2\text{/L})}{\text{Post-Oxygenator Blood Oxygen Content}} = \underset{(\text{mL } O_2\text{/g Hb})}{1.34} \times \underset{(\text{g/dL})}{10.5} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \times \underset{(\text{decimal})}{1.00} + \left(\underset{(\text{mm Hg})}{300} \times \underset{(\text{mL O2/dL/mm Hg})}{0.0031} \times \underset{\text{unit conversion}}{\frac{10 \text{ dL}}{1 \text{ L}}} \right) = \underset{(\text{mL } O_2\text{/L})}{150.0}$$

Step 2 Calculate Total Flow

$$\text{Total Flow} = 4 \text{ L/min} \times \frac{150.0 - 91.3}{125.4 - 91.3} = \underset{(\text{L/min})}{6.9}$$

VV-ECMO Flow Rate of 4L/min (L/min)

$$\underset{(\text{L/min})}{\text{Venous Flow}} = \underset{(\text{L/min})}{\text{Total Flow}} - \underset{(\text{L/min})}{\text{VV-ECMO Flow}} = \underset{(\text{L/min})}{2.9}$$

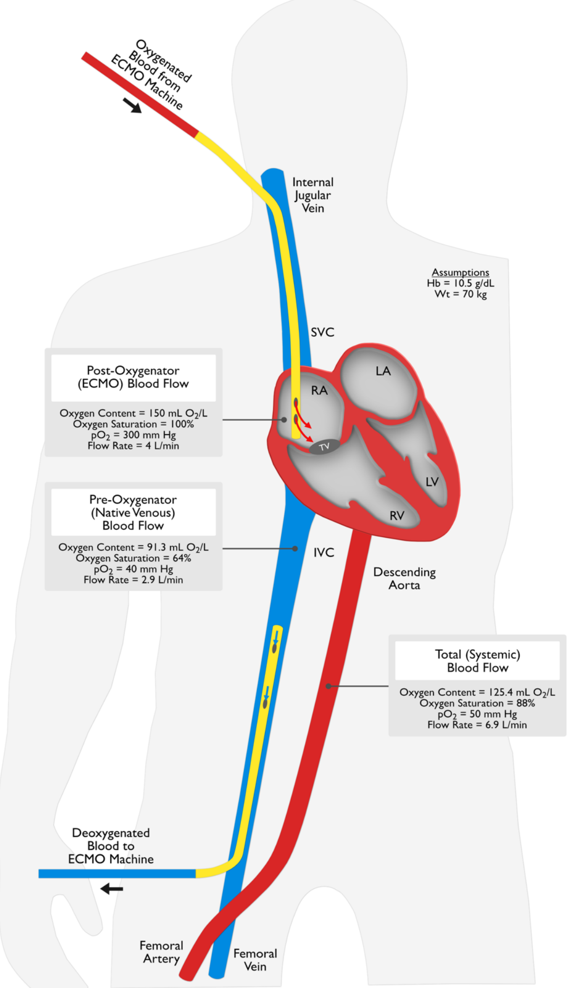
Step 3 Calculate Oxygen Delivery/ Consumption Ratio

$$\underset{(\text{mL } O_2\text{/min})}{\text{Oxygen Delivery}} = \underset{(\text{mL } O_2\text{/L})}{125.4} \times \underset{(\text{L/min})}{6.9} = 865.3$$

$$\underset{(\text{mL } O_2\text{/min})}{\text{Oxygen Consumption}} = \underset{(\text{kg})}{70} \times \underset{(\text{mL } O_2\text{/min/kg})}{3} = 210.0$$

$$\text{Oxygen Delivery/Consumption Ratio} = \frac{865.3}{210.0} = 4.1$$

Mixing of Venovenous Extracorporeal Membrane Oxygenation (VV-ECMO) Blood Flow with Native Venous Blood Flow



Assumptions
Hb = 10.5 g/dL
Wt = 70 kg

Post-Oxygenator (ECMO) Blood Flow
Oxygen Content = 150 mL O_2/L
Oxygen Saturation = 100%
pO_2 = 300 mm Hg
Flow Rate = 4 L/min

Pre-Oxygenator (Native Venous) Blood Flow
Oxygen Content = 91.3 mL O_2/L
Oxygen Saturation = 64%
pO_2 = 40 mm Hg
Flow Rate = 2.9 L/min

Total (Systemic) Blood Flow
Oxygen Content = 125.4 mL O_2/L
Oxygen Saturation = 88%
pO_2 = 50 mm Hg
Flow Rate = 6.9 L/min

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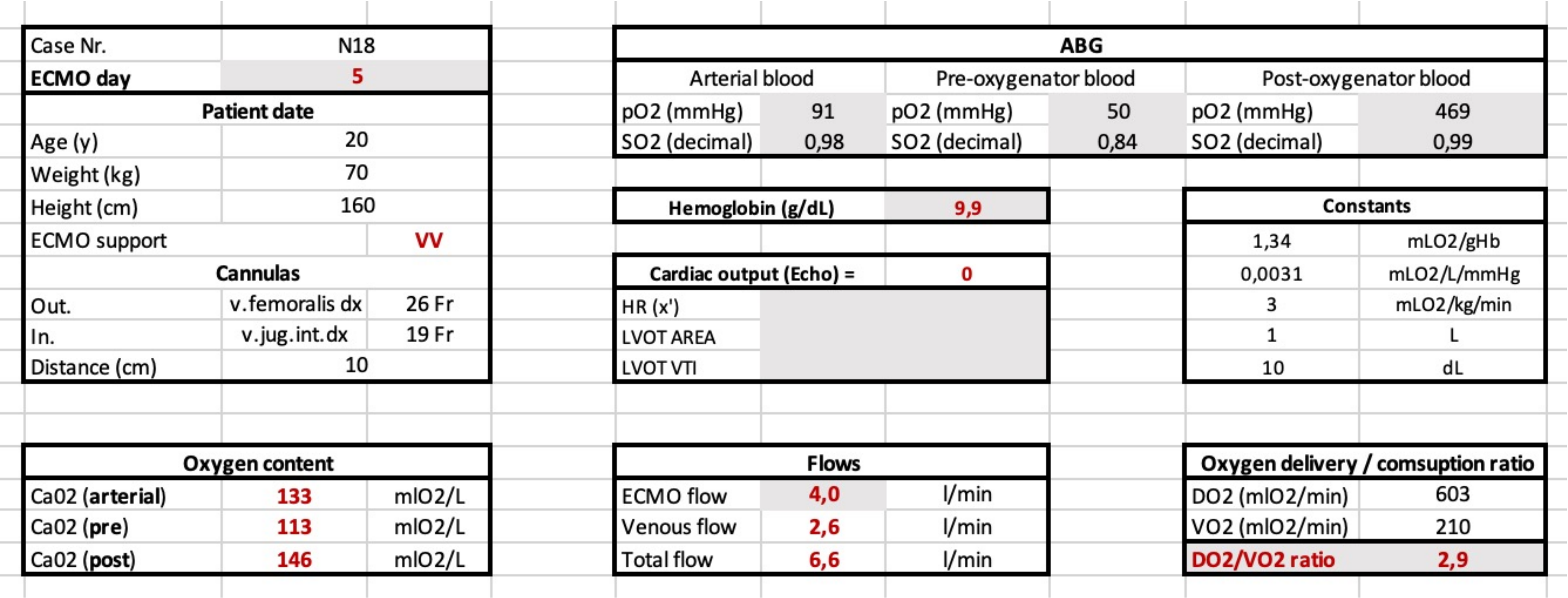
Example from Our Department



Case Nr.	N18	
ECMO day	**5**	
Patient date		
Age (y)	20	
Weight (kg)	70	
Height (cm)	160	
ECMO support		**VV**
Cannulas		
Out.	v.femoralis dx	26 Fr
In.	v.jug.int.dx	19 Fr
Distance (cm)	10	

ABG					
Arterial blood		Pre-oxygenator blood		Post-oxygenator blood	
pO2 (mmHg)	91	pO2 (mmHg)	50	pO2 (mmHg)	469
SO2 (decimal)	0,98	SO2 (decimal)	0,84	SO2 (decimal)	0,99

Hemoglobin (g/dL)	**9,9**

Cardiac output (Echo) =	**0**
HR (x')	
LVOT AREA	
LVOT VTI	

Constants	
1,34	mLO2/gHb
0,0031	mLO2/L/mmHg
3	mLO2/kg/min
1	L
10	dL

Oxygen content		
Ca02 (**arterial**)	**133**	mlO2/L
Ca02 (**pre**)	**113**	mlO2/L
Ca02 (**post**)	**146**	mlO2/L

Flows		
ECMO flow	**4,0**	l/min
Venous flow	**2,6**	l/min
Total flow	**6,6**	l/min

Oxygen delivery / comsuption ratio	
DO2 (mlO2/min)	603
VO2 (mlO2/min)	210
DO2/VO2 ratio	**2,9**

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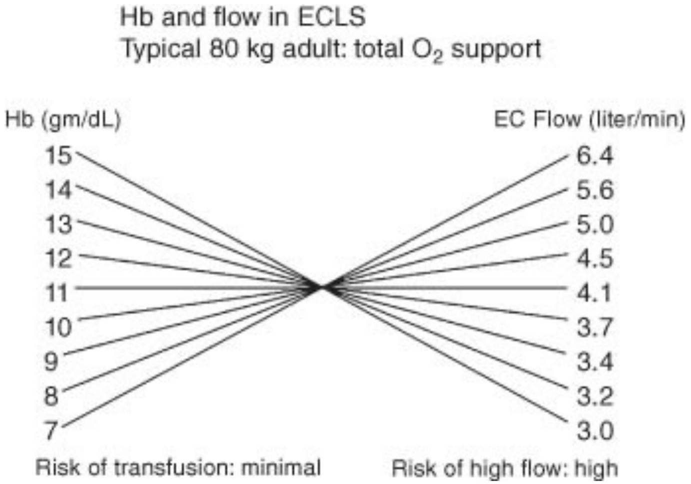
ECMO Management for Patients Needs

- **Ventilation setup**
  - NO IDEAL setups, only recommendations and protective strattegies
  - Turning up the ventilator FiO2 or airway pressure will not help
- ↑ **Blood oxygen content**
  - ↑ ECMO flow rate
  - ↑ haemoglobin/ haematocrit (up to 12 – 14 g/dL)
- ↓ **Recirculation**
  - ↑ distance between cannulas
- ↓ **Oxygen consumption**
  - ↑ sedation
  - Therapeutic hypothermia
  - Neuromuscular blockage
- **Cardiac output / intrapulmonal shunt**
  - B-blockers
- *Switch to venoarterial or hybrid configuration*



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Take Home Messeges

- **VO2/DO2 should be calculated for every patients on ECMO**

- Adjust the ECMO variables and the patient variables to maintain DO2/VO2 =/> 3:1;
- Non damaging ventilation: (FiO_2 0.3 – 0.5, CPAP 15-20cm H2O, RR 5 – 10, Pplat<25);
- Titrated ECMO flow to maintain SaO2 90%;
- Adjust the sweep gas to keep the $PaCO_2$ 40 mmHg;
- If low SaO_2 with adequate ECMO flow -> recirculation/oxygenator disfunction or high VO_2 (↑ *ECMO flow? ↑Hb? Temp.? ↓ CO ? – which one?)*
- **Allow healing of the lungs and rest**

Take Home Messeges

- When the patient is stable (*usually 6-12 hours*) determine the variables of O2 kinetics:
  - If oxygen supply is adequate (DO2:VO2 over 3) no changes are necessary;
  - If oxygen supply is inadequate (DO2:VO2 under 3) and the patient is anaemic, transfuse to a higher haemoglobin;
  - If DO2 is still inadequate change the drainage cannula to a larger size and increase flow

- Remember:
  - DO2 ↑, if ↑ Hgb / CO / PaO2
  - VO2↓, if – hypothermia, anaesthesia, decrease work of breathing

Thank You!

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