MECHANICAL CIRCULATORY SUPPORT REFERENCE
BY RISHI KUMAR, MD - HTTPS://RK.MD

Abbreviations: afterload (**AL**), aorta (**Ao**), aortic valve (**AV**), chronic thromboembolic pulmonary hypertension (**CTEPH**), coronary perfusion pressure (**CPP**), extracorporeal membrane oxygenation (**ECMO**), left atrium (**LA**), left ventricle (**LV**), left ventricular end diastolic pressure (**LVEDP**), main pulmonary artery (**mPA**), mean arterial pressure (**MAP**), mitral valve (**MV**), pulmonary artery occlusion pressure (**PAOP**), pulmonary vascular resistance (**PVR**), ventricular assist device (**VAD**), United Network for Organ Sharing (**UNOS**)

	PARAMETER	EQUATION	NORMAL VALUES
Hemodynamic	Heart Rate (HR)	-	60-100
	Stroke Volume (SV)	(CO / HR) x 1000	50 - 100 cc/beat
	Stroke Volume Index (SVI)	SV / BSA	40 - 60 cc/beat/m^2
	Cardiac Output (CO)	HR x SV	4 - 8 L/min
	Cardiac Index (CI)	CO / BSA	2.5 - 4.0 L/min/m^2
	Shock Index	HR / SBP	0.5 - 0.7 beats/mmHg
	Cardiac Power Output (CPO)	(MAP x CO) / 451	> 0.6 Watts
	PA Pulsatility Index (PAPi)	(PASP - PADP) / RA	< 0.9 suggests RVF
	LV Stroke Work Index (LVSWI)	0.0136 x SVI x (MAP - PAOP)	50 - 60 g/m^2/beat
	RV Stroke Work Index (RVSWI)	0.0136 x SVI x (mPAP - CVP)	5 - 10 g/m^2/beat
Pressure	Systolic BP (SBP)	-	90 - 120 mmHg
	Diastolic BP (DBP)	-	60 - 90 mmHg
	Pulse Pressure (PP)	SBP - DBP	40 - 70 mmHg
	Mean Arterial Pressure (MAP)	(2/3 x DBP) + (1/3 x SBP)	60 - 100 mmHg
	Central Venous Pressure (CVP) or Right Atrial Pressure (RAP)		2 - 6 mmHg
	Right Ventricle (RV)	-	15 - 25 mmHg / 0 - 8 mmHg
	Pulmonary Artery (PA)	-	15 - 25 mmHg / 8 - 15 mmHg
	Mean PA Pressure (mPAP)	(2/3 x PADP) + (1/3 x PASP)	9 - 18 mmHg
	PA Occlusion Pressure (PAOP)	-	6 - 12 mmHg
	Left Atrium	-	6 - 12 mmHg
	RAP:PAOP Ratio	RAP / PAOP	> 0.63 suggests RVF after LVAD
	Coronary Perfusion Pressure (CPP)	DBP - LVEDP (for LV) or DBP - RVEDP (for RV)	60 - 80 mmHg
Resistance	SVR	[(MAP - CVP) / CO] x 80	800 - 1200 dynes-sec/cm^5
	SVRI	[(MAP - CVP) / CI] x 80	1500 - 2400 dynes-sec/cm^5
	PVR	[(mPAP - PAOP) / CO] x 80	50 - 200 dynes-sec/cm^5
	PVRI	[(mPAP - PAOP) / CI] x 80	50 - 225 dynes-sec/cm^5
Gas Exchange And Delivery	FiO_2	fraction of inspired O_2 = 0.21 - 1.00 (often given as fraction, 0.21 = room air)	
	P_b	barometric pressure = 0 - 760 mmHg (760 mmHg at sea level)	
	Respiratory Quotient (RQ)	0.7 (only lipids), 0.8 (balanced diet), 1.0 (only carbs)	
	Alveolar Gas Equation	$P_AO_2 = F_iO_2 (P_b - P_{H2O}) - P_aCO_2 / RQ$ P_{H2O} ~47 mmHg at sea level	~100 mmHg at sea level
	P_ACO_2 Equation	$P_ACO_2 = (VCO_2 \times 0.863) / V_A$	
	P/F Ratio	P_aO_2 / F_iO_2	> 400
	A-a Gradient	$P_AO_2 - P_aO_2$	7 mmHg (young) 15 mmHg (elderly)
	Respiratory Index	$RI = (P_AO_2 - PaO2) / P_aO_2$	< 0.4
	Arterial O_2 Content	$C_aO_2 = (1.34 \times [Hb] \times [S_aO_2]) + (0.003 \times P_aO_2)$	17 - 20 cc O_2/100 cc
	Mixed Venous O_2 Content	$C_vO_2 = (1.34 \times [Hb] \times [S_vO_2]) + (0.003 \times P_vO_2)$	12 - 15 cc O_2/100 cc
	Arteriovenous Difference	$C_aO_2 - C_vO_2$	4 - 5 cc O_2/100 cc
	Fick O_2 Consumption	$VO_2 = 10 \times CO \times (C_aO_2 - C_vO_2]$	3.5 cc O_2/kg/min
	Fick Cardiac Output	$CO = VO_2 / [10 \times (C_aO_2 - C_vO_2)]$	4 - 8 L/min

Device	Mechanism	Inflow → Outflow	Max Flow (L/min)	Max Pump Speed (rpm)	MAP	AL	LVEDP	PAOP	CPP	LV Unloading	O_2 Demand
IABP	Ao counter-pulsation	---	0.5	N/A	↑	↓	↓	↓	↑	↑	↓
Impella 2.5	axial	LV → Ao	2.5	51,000	↑↑	↓	↓↓	↓	↑	↑↑	↓↓
Impella CP	axial	LV → Ao	4.3	51,000	↑↑	↓	↓↓	↓	↑	↑↑	↓↓
Impella 5.0	axial	LV → Ao	5.0	33,000	↑↑	↓	↓↓↓	↓	↑↑	↑↑↑	↓↓
Impella 5.5	axial	LV → Ao	6.0	33,000	↑↑	↓	↓↓↓	↓	↑↑	↑↑↑	↓↓
Impella RP	axial	IVC → mPA	4.5	33,000	---	---	---	---	---	---	---
TANDEMHEART	centrifugal	LA → femoral art.	4.0	7,500	↑↑	↑	↓↓↓	↓	↔	↑↑↑	↓
CentriMag	centrifugal	LA/LV → Ao RA → mPA	10	5,500	↑↑	↓	↓↓	↓	↑↑	↑↑	↓↓
VA-ECMO	centrifugal	variable	7.0	5,000	↑↑	↑↑	↔	↔	↔	---	↔
HeartMate II LVAD	axial continuous	LV apex → Ao	10	6,000 - 15,000	LVADs can be placed as a bridge-to-transplantation, bridge-to-recovery, or destination therapy. The HVAD's Lavare cycle creates periodic speed adjustments (decelerates for 2 s, accelerates for 1 s) similar to the HMIII's intermittent washing to facilitate pump washing and reduce blood stasis. **Pump speed** is the only adjustable parameter, and flow is related to preload, afterload, viscosity, etc. Pulsatility is dependent on LV loading and native contractility.						
HeartWare HVAD	centrifugal Lavare cycle	LV apex → Ao	10	1,800 - 4,000							
HeartMate III LVAD	centrifugal q2s washing	LV apex → Ao	10	2,000 - 5,500							

UNOS HEART TRANSPLANT STATUSES

Old	New	Criteria
1A	1	VA-ECMO
		Non-dischargeable BiVAD
		MCSD with life threatening arrhythmias
	2	IABP
		Sustained VT or VF
		Dischargeable BiVAD, TAH, RVAD
		MCSD with malfunction
		Percutaneous endovascular MCS
	3	Dischargeable LVAD for 30 days
		MCSD with complication (infection, hemolysis, bleeding, AI, pump thrombosis)
		IV inotrope infusion + hemodynamic monitoring
1B	4	Inotropes without hemodynamic monitoring
		Stable LVAD
		Ischemia with intractable angina
		CHD
		Hypertrophic CM
		Restrictive CM
		Retransplant
2	5	**Combined** organ transplants
	6	Remaining **active** candidates

PULMONARY HYPERTENSION (PH)

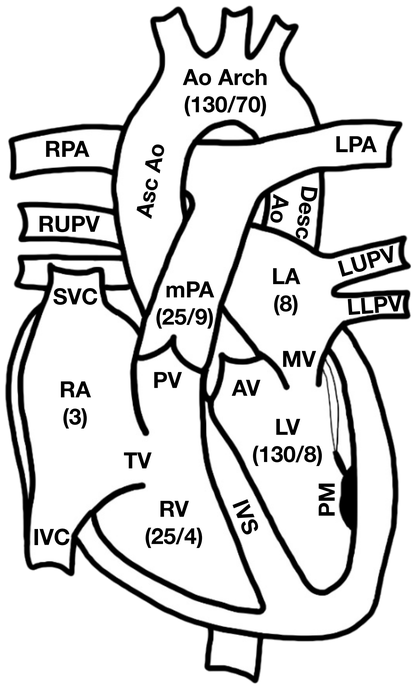
WHO Group	Mechanism	Clinical Definition	Hemodynamic	Examples
1	Vascular remodeling of pulmonary arteries	precapillary	mPAP > 20 mmHg PAOP ≤ 15 mmHg PVR > 2 WU	idiopathic, medications, HIV, connective tissue disorders
2	Left-sided heart disease causing back up of blood flow	postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg	left heart failure, aortic valve disease, mitral valve disease
		isolated postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg PVR ≤ 2 WU	
		combined pre and postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg PVR > 2 WU	
3	Chronic lung disease causing hypoxemia	precapillary	mPAP > 20 mmHg PAOP ≤ 15 mmHg PVR > 2 WU	COPD, ILD, sleep apnea
4	CTEPH	precapillary	mPAP > 20 mmHg PAOP ≤ 15 mmHg PVR ≥ 2 WU	chronic pulmonary emboli
5	Unclear and multifactorial	precapillary	mPAP > 20 mmHg PAOP ≤ 15 mmHg PVR > 2 WU	sarcoidosis, chronic hemolytic anemia, thyroid disorders, sickle cell anemia, splenectomy, mediastinal tumors, chronic renal failure on hemodialysis
		postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg	
		isolated postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg PVR ≤ 2 WU	
		combined pre and postcapillary	mPAP > 20 mmHg PAOP > 15 mmHg PVR > 2 WU	

MECHANICAL CIRCULATORY SUPPORT REFERENCE
BY RISHI KUMAR, MD - HTTPS://RK.MD

Sources: United Network For Organ Sharing (UNOS)' Organ Procurement And Transplantation Network (OPTN), ABIOMED (https://www.abiomed.com/), *Mechanical Circulatory Support: Principles and Applications* by Joyce et al.

SCAN TO SHARE

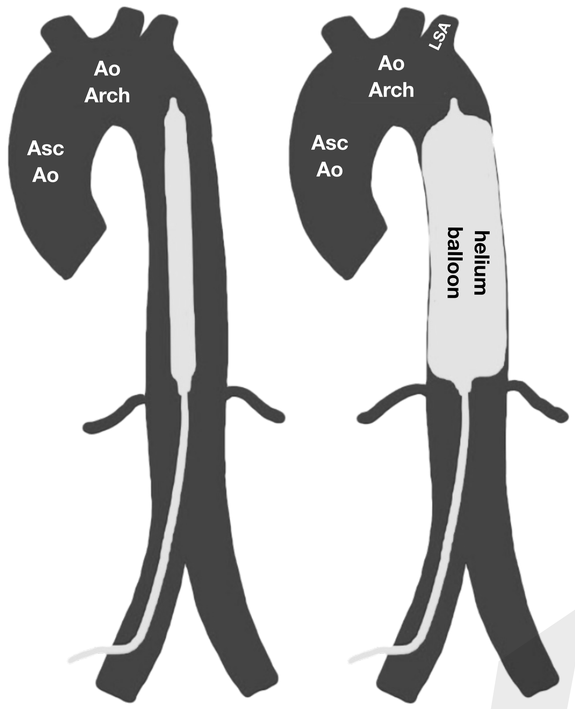
NORMAL INTRACARDIAC PRESSURES



Chambers/Vessels (normal mean chamber pressure in mmHg)
Blood Flow: SVC/IVC → RA → RV → mPA → LA → LV → Asc Ao

Abbreviations: superior/inferior vena cava (**SVC/IVC**), right/left atrium (**RA/LA**), right/left ventricle (**RV/LV**), main/right/left pulmonary artery (**mPA/RPA/LPA**), right upper/left upper/left lower pulmonary vein (**RUPV/LUPV/LLPV**), tricuspid/pulmonic/mitral/aortic valve (**TV/PV/MV/AV**), interventricular septum (**IVS**), papillary muscle (**PM**), aorta (**Ao**)

INTRA-AORTIC BALLOON PUMP (IABP)

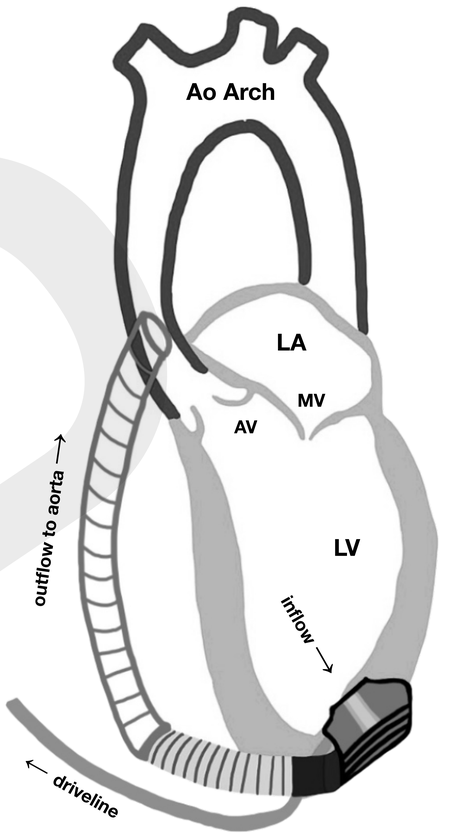


- **Trigger:** EKG, arterial waveform, internal
- **Frequency:** 1:1 (every beat augmented), 1:3 (every third), etc.
- **Augmentation:** should be above systolic peak pressure, affected by balloon volume, heart rate, preload, aortic compliance

The IABP uses counter-pulsation to increase coronary perfusion pressure by rapidly **inflating** a balloon with helium during **diastole** and **deflating** it during **systole**. The tip of the IABP is positioned just distal to the left subclavian artery (**LSA**).

LEFT VENTRICULAR ASSIST DEVICE (LVAD)

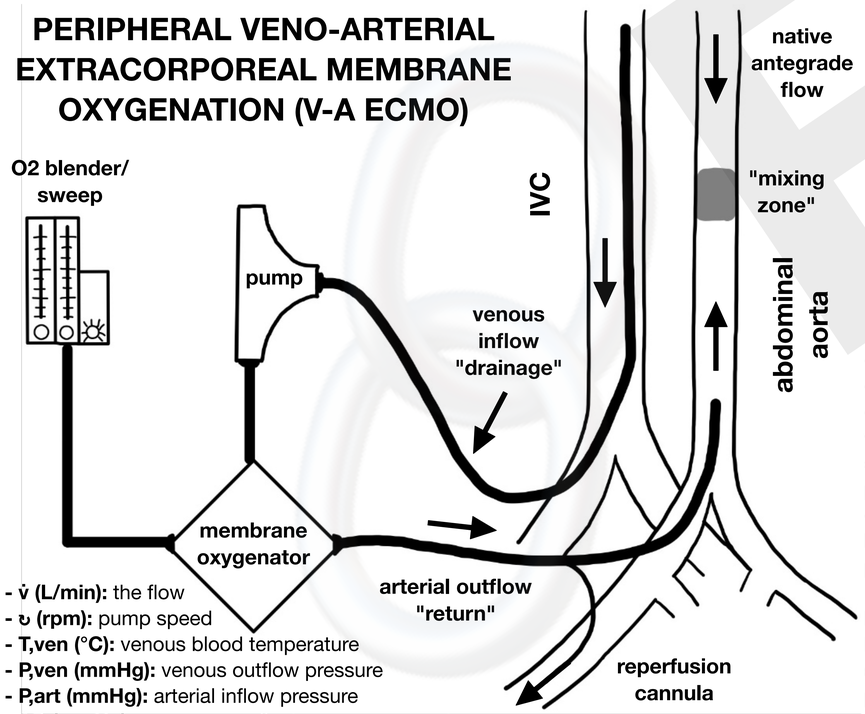
Event	MAP	Pump Power	Pump Pulsatility	Pump Flow	Echo Findings	Management
Suction	↓	↓	↓	↓	Underfilled LV	Volume, ↓ pump speed
Hypervolemia	↑	↑	↑	↑	Distended LV	↑ pump speed
RHF	↔/↓	↓	↔/↓	↓	Dilated RA/RV, worse TR	Diurese, inotrope
Vasoconstriction	↑	↓	↔/↑	↓	Normal	Vasodilator
Vasodilation	↓	↑	↔/↓	↑	Normal, potentially hyperdynamic	Vasopressor
Pump Thrombosis	↓	↑	↓	↓	Dilated LV, worse MR	Thrombolytics, emergent pump exchange
Tamponade	↓	↓	↓	↓	RA systolic collapse, RV diastolic collapse, pericardial fluid	Volume, ↑ pump speed, pericardial window/drain



- **Speed (rpm):** pump speed - only directly adjustable parameter
- **Flow (L/m):** pump flow - affected by pump speed, preload, afterload, viscosity
- **Power (W):** measure of the current/voltage driving the motor
- **Pulsatility Index (PI):** degree of native LV pulsatility, calculated from flow (which, in turn, is a calculated number)

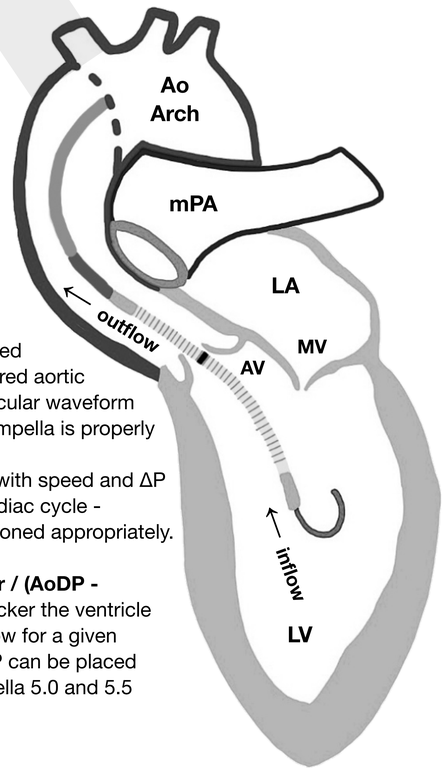
LVADs are placed for a bridge-to-transplantation (**BTT**), bridge-to-candidacy (**BTC**), or destination therapy (**DT**). During implantation, pump speeds are increased to effectively unload the LV while maintaining some degree of pulsatility (aortic valve opening) and midline interventricular septal positioning. **Suction events** occur when LVAD inflow is decreased due to an obstruction or hypovolemia. Remember, not all suction events require fluid - consider decreasing the pump speed and other etiologies of decreased LV preload like acute right heart failure or tamponade.

PERIPHERAL VENO-ARTERIAL EXTRACORPOREAL MEMBRANE OXYGENATION (V-A ECMO)



- **v̇ (L/min):** the flow
- **ʊ (rpm):** pump speed
- **T,ven (°C):** venous blood temperature
- **P,ven (mmHg):** venous outflow pressure
- **P,art (mmHg):** arterial inflow pressure
- **ΔP (mmHg):** pressure gradient across oxygenator
- **Inflow:** cannula(s) through which blood is **drained** from the patient
- **Outflow**: cannula(s) through which blood is **returned** to the patient

IMPELLA



- **v̇ (L/min):** the flow
- **P1 to P8 (power):** pump speed
- **Placement Signal (mmHg):** red aortic waveform and white left ventricular waveform demonstrate pulsatility when Impella is properly positioned
- **Motor Current (mA):** varies with speed and ΔP between LV and Ao during cardiac cycle - pulsatile when Impella is positioned appropriately.

Remember that flow ~ power / (AoDP - LVEDP). In other words, the sicker the ventricle (high LVEDP), the better the flow for a given power. Impella 2.5, CP, and RP can be placed **percutaneously** whereas Impella 5.0 and 5.5 require a **surgical** cut-down.

CVP/RA WAVEFORMS

'a' wave (end diastole) right atrial (RA) contraction

Lost in atrial fibrillation/flutter

↑ 'a' wave in tricuspid/pulmonic stenosis and RV failure due to ↑ resistance to forward flow

"Cannon" 'a' waves in junctional rhythm, V-tach, 3° block from RA contraction against closed tricuspid valve (TV) generating large reflection wave back into RA

'c' wave (early systole) TV cusps bulging into RA

Tricuspid regurgitation (TR) causes fusion of 'c' and 'v' waves with blunting of 'x' descent

'v' wave (late systole) rapid filling of RA

↑ 'v' wave in TR (reaches RVSP) from regurgitant jet ↑ RA pressure

'x' descent (mid systole) RA relaxation

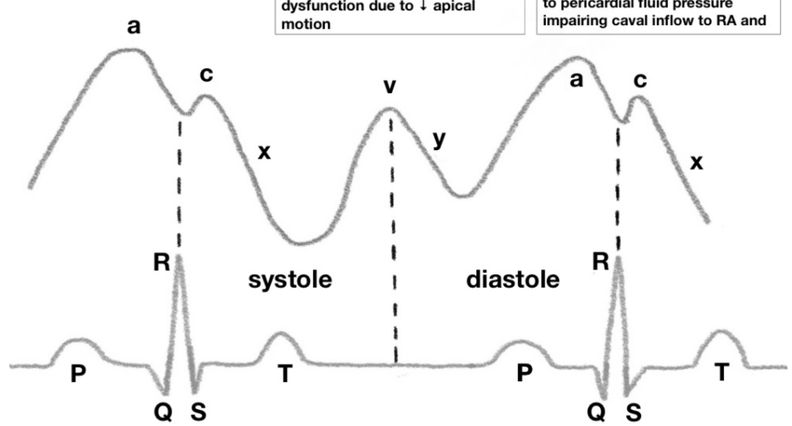
↑ 'x' descent in constrictive pericarditis

↓ 'x' descent with TR as this jet ↑ RA pressure. Suggests RV dysfunction due to ↓ apical motion

'y' descent (early diastole) early ventricular filling

↑ 'y' descent in constrictive pericarditis and RV failure

↓ 'y' descent in tamponade due to pericardial fluid pressure impairing caval inflow to RA and



This reference sheet is provided "as is" with potential faults and errors. As such, I am not responsible for any outcomes. Contact me with errors/suggestions at rishi@rk.md.
Copyright © 2021-2023 - Rishi Kumar, MD
Last Revised: 9/22/2023