TCTAP 2024-4-27

Prof. Wei-Chun Huang

MD, PhD, FESC, FACC, FHQS

Hemodynamics in CHIP PCI

Cardiogenic Shock

Kaohsiung Veterans General Hospital, TAIWAN

TSCI 臺灣介入性心臟血管醫學會 TAIWAN SOCIETY OF CARDIOVASCULAR INTERVENTIONS

TAMIS 台灣心肌梗塞學會 Taiwan Myocardial Infarction Society

黃偉春醫師

Wei-Chun Huang , MD, PhD, FESC, FACC, FHQS

- Chief, PH Center, Kaohsiung Veterans General Hospital, TAIWAN
- Professor, School of medicine and science, Fooyin University
- Honorary President, TAiwan Myocardial Infarction Society TAMIS
- President, Taiwan Association of Caring PAH
- Executive Director. Taiwan Society of Cardiology
- Director, Taiwan Heart Foundation / Taiwan Society of Cardiovascular Intervention
- Director, Taiwan Society of Critical Care Medicine/ Taiwan PAH Association
- Judging Panel, National Medical Quality Award/ National United Circle Quality Award
- Fellow, International Society for Quality in Healthy Care, ISQua
- Committee, The American College of Cardiology, ACC, Heart failure Educational Council

黃偉春醫師

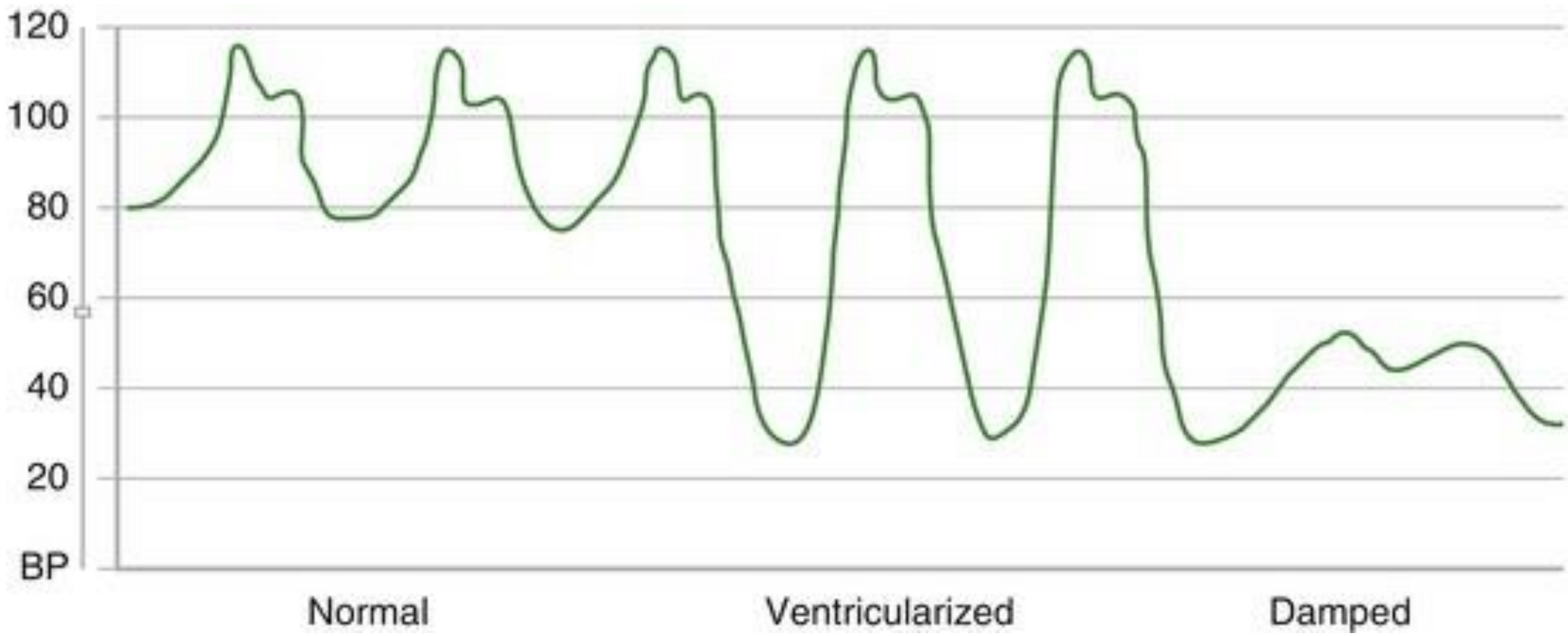
Dr. Wei-Chun Huang , MD, PhD, FESC, FACC, FHQS

- The Fellow of the American College of Cardiology (FACC)
- The Fellow of European Society of Cardiology (FESC)
- Country Champion of Taiwan, Stent Save a Life
- Fellow, International Society for Quality in Healthy Care, ISQua
- Committee, The American College of Cardiology, ACC, Heart failure Educational Council

Hemodynamics in cath lab

- Pressure value
- Pressure contour (waveforms)
- Cardiac output
- Vascular resistance
- Oxygenation
- Shunt quantification

Pressure, Damping and Ventricularization

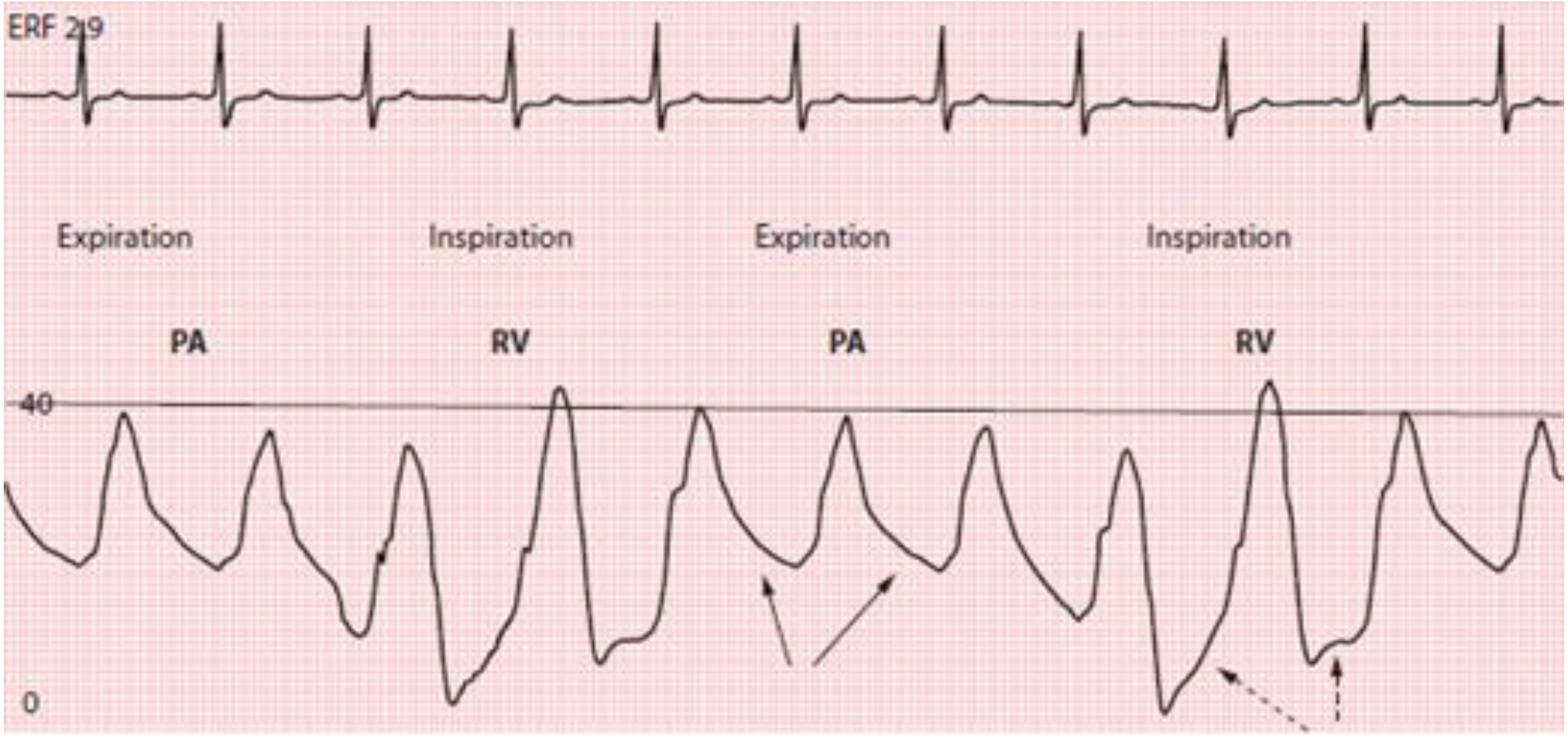


Source of error

- Tachycardia
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Catheter tip positioned too proximally PA

- Inspiration, the catheter tip moves back into the RV



Source: Jesse B. Hall, Gregory A. Schmidt, John P. Kress: *Principles of Critical Care*, 4th Edition: www.accessmedicine.com

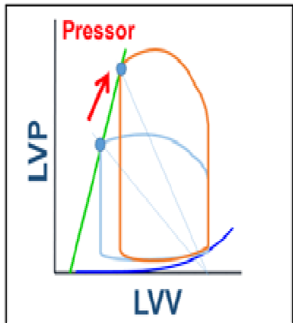
Push-dose norepinephrine in cath room

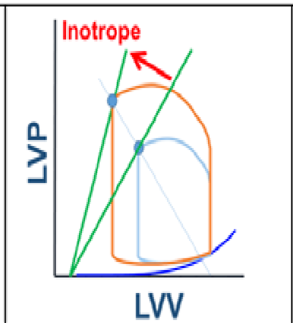
- Norepinephrine
  - A potent alpha agonist with modest beta agonist
  - Induces vasoconstriction
  - Increases blood pressure
  - Increases myocardial contractility
  - Lower risk of tachycardia
- Rapid onset (<1 minute)
- Short duration of action (1-2 minutes)
- Optimal dosing regimen: unknown
  - Ranged from 3-100 mcg every 1 to 2 minutes

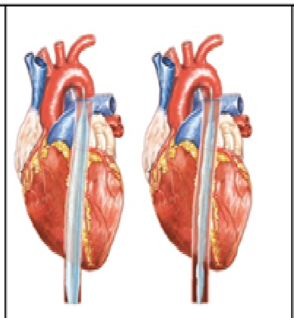
Med Sci Monit 2019;25:1093-1101; J Am Coll Cardiol 2018;72(2):173-182.

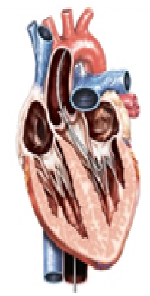
Value of Hemodynamic Monitoring in Patients With Cardiogenic Shock Undergoing Mechanical Circulatory Support

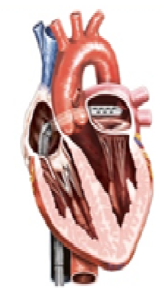
Mechanisms, technical requirements, and hemodynamic responses of various mechanical circulatory support devices

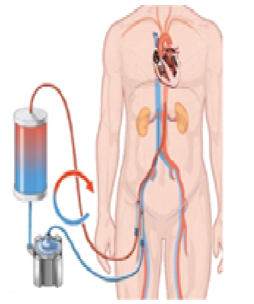












	Vasopressor	Inotrope	IABP	IMPELLA	TANDEMHEART	VA-ECMO
Mechanism	Peripheral vasoconstriction	Increased myocyte calcium cycling	Aortic counter-pulsation	Left ventricle (LV) to aorta transvalvular circulatory support (LVADs)	Left atrium (LA) to arterial circulatory support	Right atrium (RA) to peripheral artery circulatory support with gas exchange unit
LV Contractility	↔ or ↑	↑	↔	↔	↔	↔
TPR	↑	↔ or ↑ or ↓	↔	↔	↔	↔
LV Flow	↓	↑	↑	↓	↓	↓
Total CO	↓	↑	↑	↑↑	↑↑	↑↑↑
CVP	↔ or ↑	↔	↔ or ↓	↔ or ↓	↔ or ↓	↓
PCWP	↔ or ↑	↔ or ↓	↔ or ↓	↓	↓	↔ or ↑
MAP	↑	↑	↑	↑↑	↑↑	↑↑
Total CPO	↔ or ↑	↑	↑	↑↑	↑↑	↑↑
PVA	↑	↑	↔ or ↓	↓↓	↔ or ↓	↑↑
MVO2	↑	↑	↓	↓↓	↔ or ↓	↑↑
Sheath size	NA	NA	7-8 French arterial	14 French arterial	15-17 French arterial 21 French Venous	15 – 17 French arterial 21-23 French venous

Circulation 2020 Apr 7;141(14):1184-1197.

Types of Hemodynamic Support in the Cath Lab

Device	IABP	TandemHeart	VA-ECMO	Impella 2.5/CP
Afterload	↓	↑	↑↑↑	↓
Systolic BP	↓	↑↑	↑↑	↑↑
Diastolic BP	↑	↑↑	↑↑	↑↑
MAP	↑	↑↑	↑↑	↑↑
Cardiac flow	↑	↑↑	↑↑	↑↑
Cardiac power	↑	↑↑	↑↑	↑↑
LVEDP	↓	↓↓	⇔	↓↓
PCWP	↓	↓↓	⇔	↓↓
LV preload	-----	↓↓	↓	↓↓
Coronary perfusion	↑	------	-----	↑
Myocardial oxygen demand	↓	⇔↓	⇔	↓↓
Hemodynamic support	↑Diastolic aortic pressure			

EVIDENCE RELATED TO PAC USE IN CS AND MCS

PRACTICE GUIDELINE

2013 ACCF/AHA Guideline for the Management of Heart Failure: Executive Summary

- **Monitoring with a PAC should be performed in patients with respiratory distress or impaired systemic perfusion when clinical assessment is inadequate**
  - **COR I, Level C**

PRACTICE GUIDELINE

2013 ACCF/AHA Guideline for the Management of Heart Failure: Executive Summary

- Invasive hemodynamic monitoring can be useful for carefully selected patients with acute HF with persistent symptoms despite empiric adjustment of standard therapies and
  - • Whose **fluid status, perfusion, or systemic or pulmonary vascular resistance** is **uncertain;**
  - • Whose **systolic pressure remains low,** or is associated with symptoms, despite initial therapy;
  - • Whose **renal function is worsening** with therapy;
  - • Who require **parenteral vasoactive agents**; or
  - • Who may need **consideration for MCS or transplantation**
  - **COR IIa, Level C**

PRACTICE GUIDELINE

2013 ACCF/AHA Guideline for the Management of Heart Failure: Executive Summary

- Routine use of invasive hemodynamic monitoring is NOT recommended in normotensive patients with acute decompensated HF and congestion with symptomatic response to diuretics and vasodilators
  - COR III, Level B

Home > Intensive Care Medicine > Article

Hemodynamic monitoring in shock and implications for management

International Consensus Conference, Paris, France, 27–28 April 2006

- **Do NOT recommend the routine use of PAC for patients in shock.**

Circulation

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REVIEW ARTICLE

PDF/EPUB

Contemporary Management of Cardiogenic Shock: A Scientific Statement From the American Heart Association

- **Consider selected use early in the treatment course in patients not responsive to initial therapy or in case of diagnostic or therapeutic uncertainty.**

The Journal of Heart and Lung Transplantation
The Official Publication of the International Society for Heart and Lung Transplantation

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ISHLT GUIDELINES | VOLUME 32, ISSUE 2, P157-187, FEBRUARY 2013
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The 2013 International Society for Heart and Lung Transplantation Guidelines for mechanical circulatory support: Executive summary

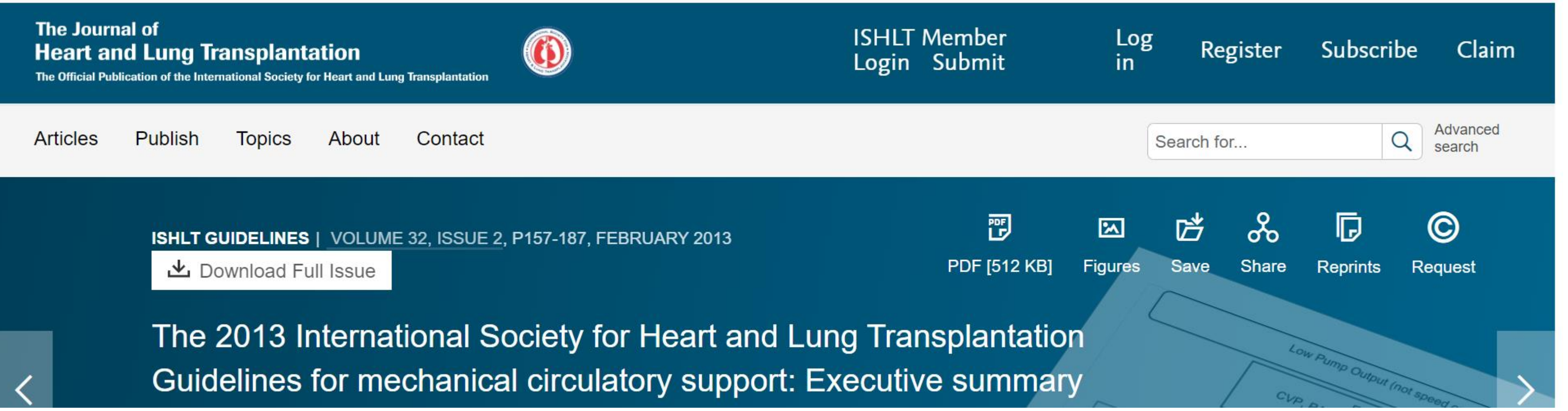
- Right heart catheterization is useful in the assessment of **persistent or recurrent HF symptoms** after MCS device placement and to evaluate for evidence of **RV failure or device malfunction**.
- COR I, Level B

The Journal of Heart and Lung Transplantation
The Official Publication of the International Society for Heart and Lung Transplantation

ISHLT GUIDELINES | VOLUME 32, ISSUE 2, P157-187, FEBRUARY 2013

The 2013 International Society for Heart and Lung Transplantation Guidelines for mechanical circulatory support: Executive summary

- **Right heart catheterization should be performed at regular intervals in patients being evaluated for or listed for heart transplant to document pulmonary artery pressures**
  - **because irreversible pulmonary hypertension is associated with early allograft dysfunction/failure after heart transplantation.**
  - **COR I, Level A**



- **Right heart catheterization should be performed to help corroborate evidence of myocardial recovery.**
- **The PAC may be left in place with serial lowering of the pump speed to confirm acceptable hemodynamics with decreasing VAD support before pump explantation.**
  - **COR IIa, Level C**

Catheterization & Cardiovascular Interventions

Valvular and Structural Heart Diseases (E-only Article)

SCAI/HFSA clinical expert consensus document on the use of invasive hemodynamics for the diagnosis and management of cardiovascular disease

- **Invasive hemodynamic assessment, with measurement of ventricular filling pressures, cardiac output, and systemic vascular resistance, is recommended for the diagnosis of cardiogenic shock.**

Catheterization & Cardiovascular Interventions

Valvular and Structural Heart Diseases (E-only Article)

SCAI/HFSA clinical expert consensus document on the use of invasive hemodynamics for the diagnosis and management of cardiovascular disease

- PAC is recommended for **acute management** of patients receiving therapy with MCS.

Catheterization & Cardiovascular Interventions

Valvular and Structural Heart Diseases (E-only Article)

SCAI/HFSA clinical expert consensus document on the use of invasive hemodynamics for the diagnosis and management of cardiovascular disease

- Pulmonary artery catheterization is useful to guide withdrawal of mechanical circulatory and pharmacologic support in patients with myocardial recovery from cardiogenic shock.
-

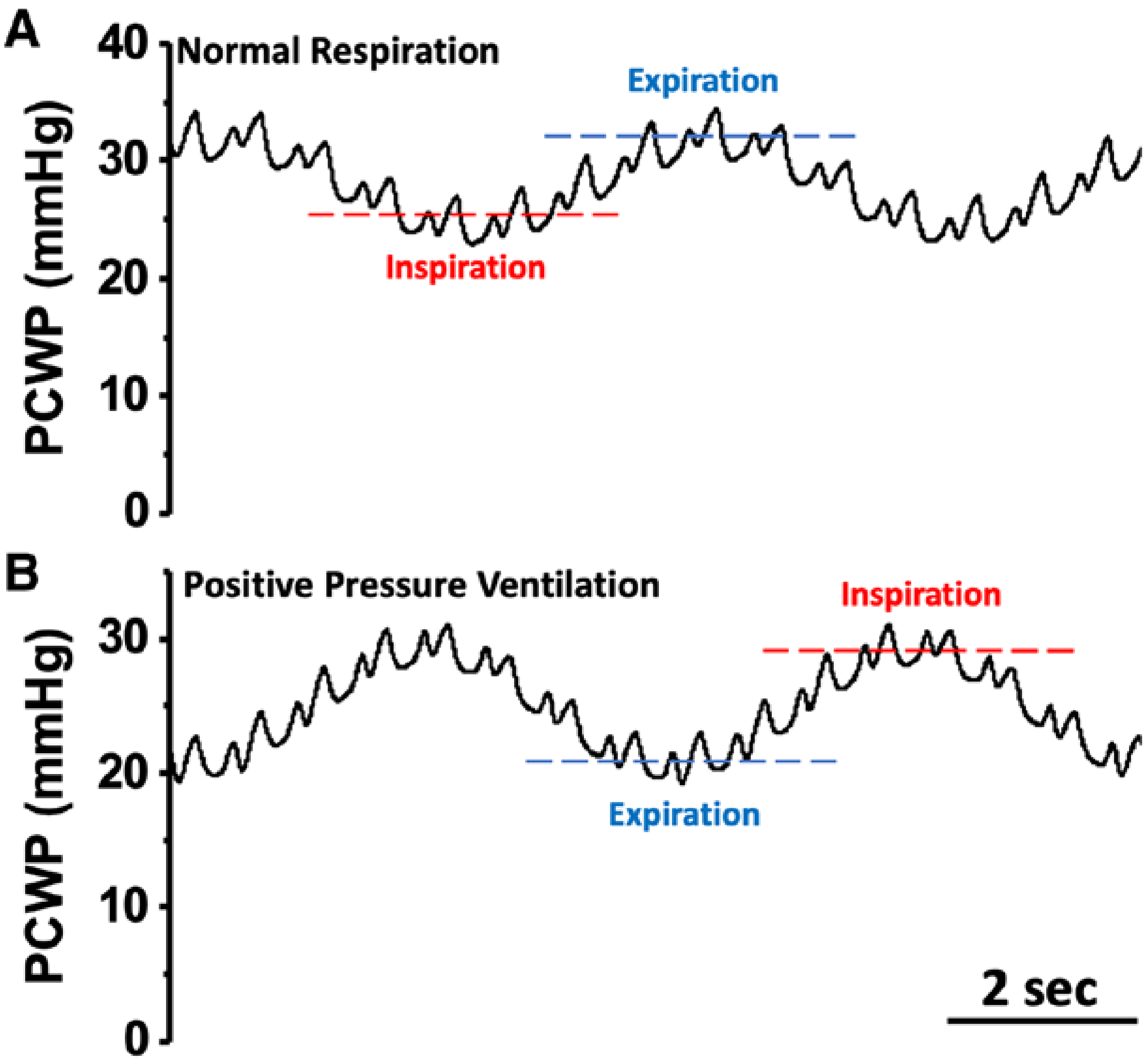
Catheterization & Cardiovascular Interventions

Valvular and Structural Heart Diseases (E-only Article)

SCAI/HFSA clinical expert consensus document on the use of invasive hemodynamics for the diagnosis and management of cardiovascular disease

- In patients without recovery of myocardial and end-organ function, hemodynamic monitoring is useful to assess candidacy for and transition to advanced HF therapies, including durable MCS and heart transplantation.

Effect of respiration on pulmonary capillary wedge pressure(PCWP) tracings



Circulation 2020 Apr 7;141(14):1184-1197.

Hemodynamic Profiles of Cardiogenic Shock Subtypes

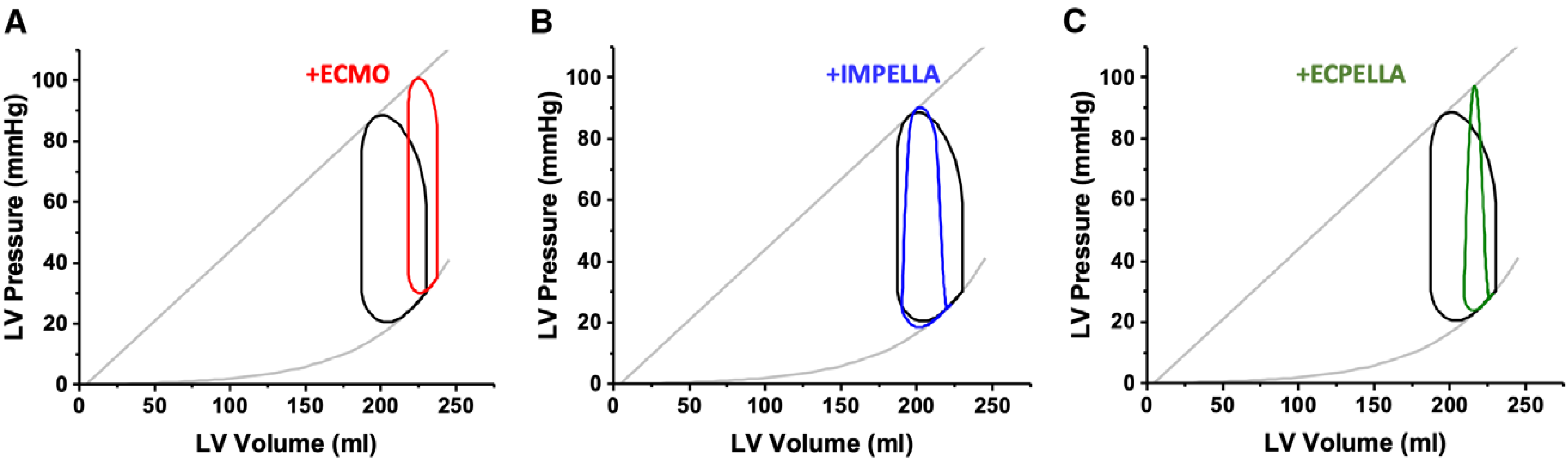
Hemodynamic Variables	Preshock Normotensive Hypoperfusion	Preshock Hypotensive Normoperfusion	LV Dominant Shock	RV Dominant Shock	B/V LV+RV Shock
Systolic arterial pressure, mm Hg	>90	<90	<90	<90	<90
CVP, mm Hg	Variable	Variable	<14	>14	>14
PCWP, mm Hg	Variable	Variable	>18	<18	Variable
CVP/PCWP	Depends on degree of LV and RV involvement	Depends on degree of LV and RV involvement	<0.86	>0.86	>0.86
PAPi (PAS – PAD)/RA[24,28–30]	Depends on degree of RV involvement	Depends on degree of RV involvement	>1.5	<1.5*	<1.5
Cardiac index, L/min/m^2	<2.2	≥2.2	<2.2	<2.2	<2.2
SVR, dynes-s/cm^{-5}	>1600	800–1600	800–1600	800–1600	800–1600
CPO, W[27]	Variable	Variable	<0.6	<0.6	<0.6

CPO, cardiac power output

Circulation 2020 Apr 7;141(14):1184-1197.

Effects of extracorporeal membrane oxygenation (ECMO), Impella, and ECMO plus an Impella device (ECPELLA) on pressure-volume loops

ECMO only | **Impella only** | **Impella+ ECMO**



ECMO only

- EDPs↑
- LV SV↓
- Effective arterial elastance↑

Impella only

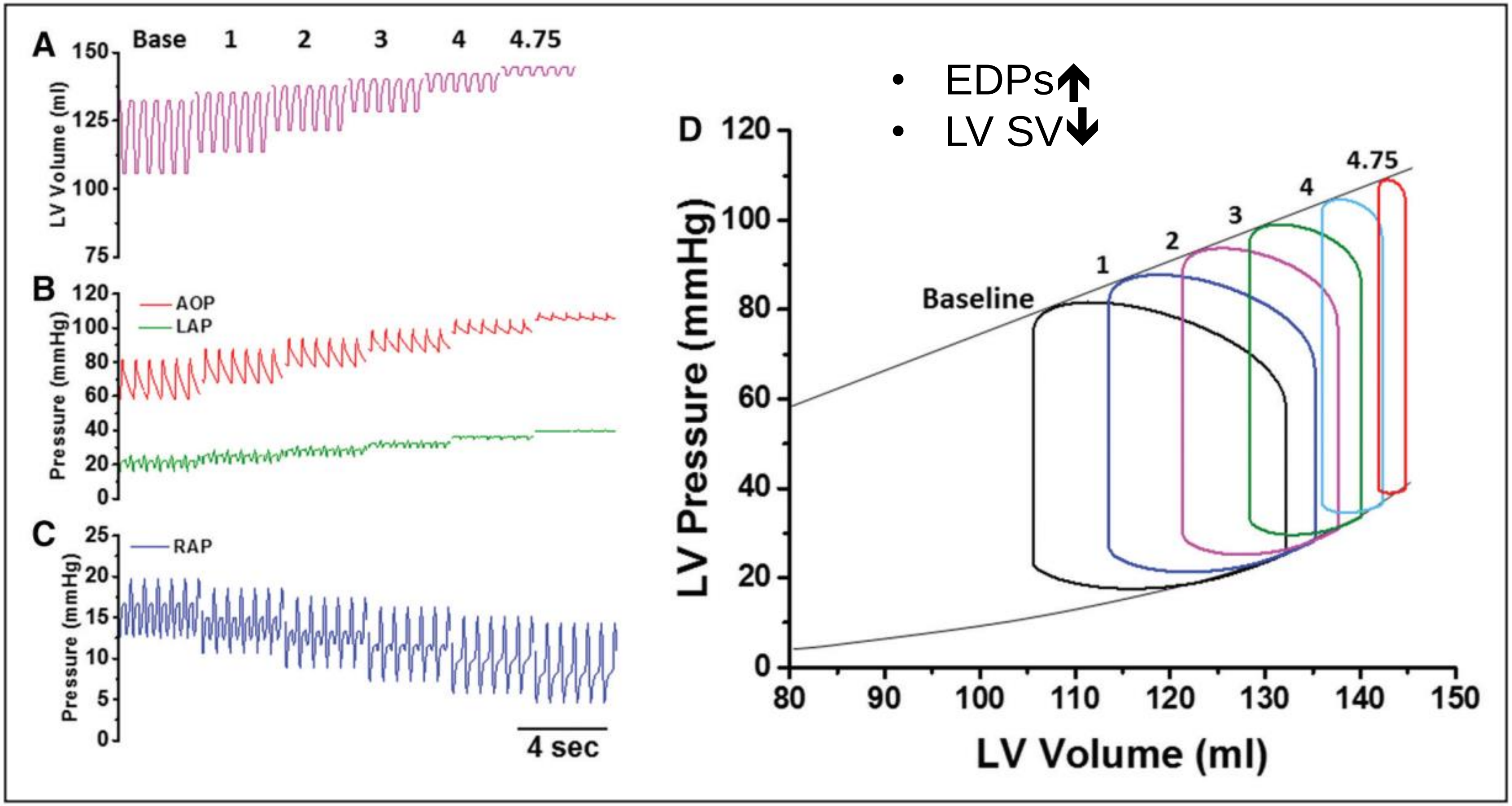
- EDP↓
- Triangulation of the loop (continuous flow across the aortic valve)
- No increase in effective arterial elastance.

Impella+ ECMO

- EDP↓
- Triangulation of the waveform.

Circulation 2020 Apr 7;141(14):1184-1197.

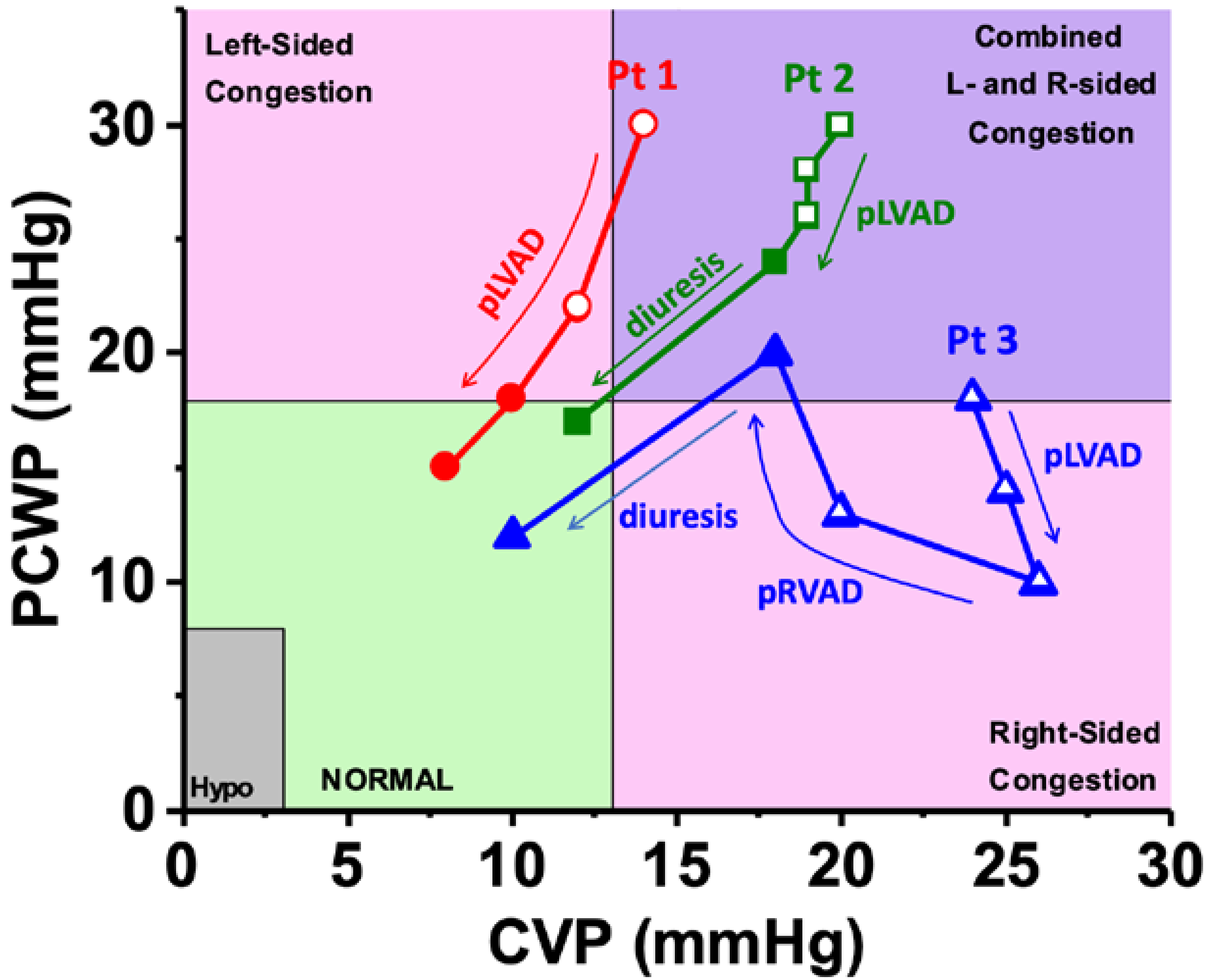
The impact of ECMO flow on right- and left-sided parameters



- EDPs↑
- LV SV↓

Circ Heart Fail. 2018;11:e004905.

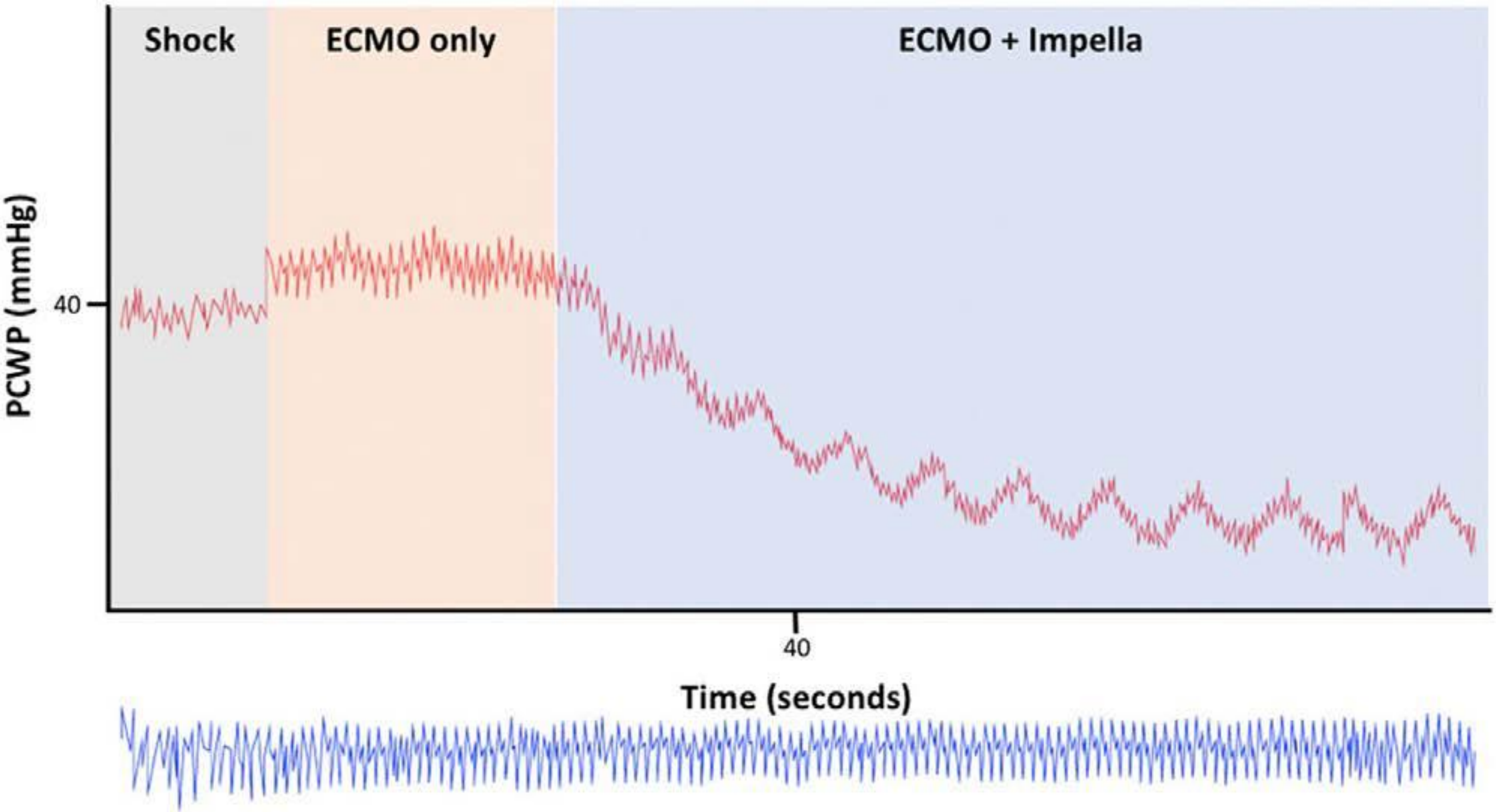
Three case examples of patients presenting with hypotension and decreased cardiac index despite inotropic support



pLVAD, percutaneous left ventricular assist device
pRVAD, percutaneous right ventricular assist device.

Circulation 2020 Apr 7;141(14):1184-1197.

Changes in pulmonary capillary wedge pressure (PCWP) with extracorporeal membrane oxygenation (ECMO) and Impella



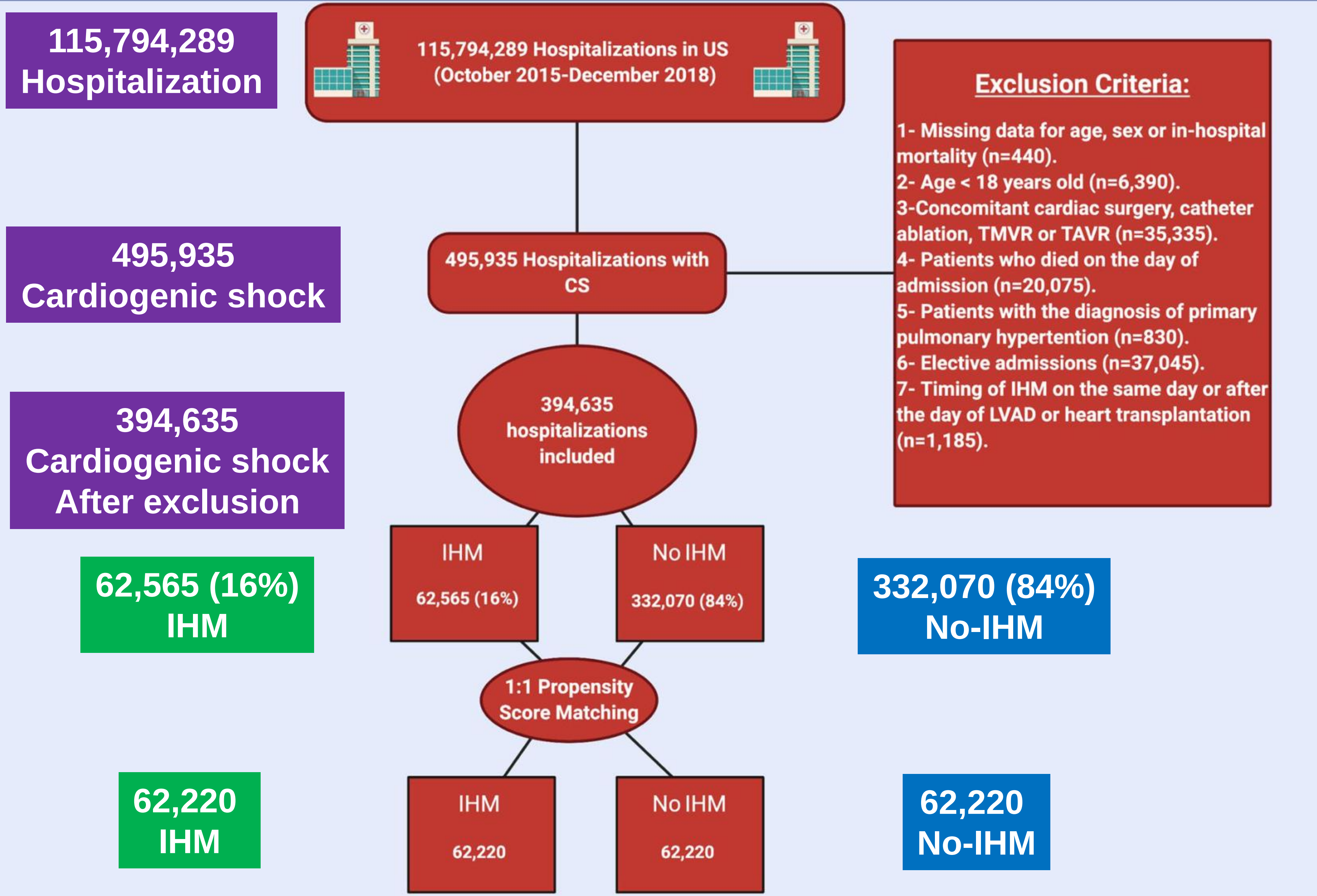
Journal of the American Heart Association

ORIGINAL RESEARCH

Invasive Hemodynamic Monitoring in Cardiogenic Shock Is Associated With Lower In-Hospital Mortality

Mohammed Osman, MD; Moinuddin Syed, MD; Brijesh Patel, DO; Muhammad Bilal Munir, MD; Babikir Kheiri, MD, MSc; Marco Caccamo, DO; George Sokos, DO; Sudarshan Balla, MD; Mir Babar Basir, DO; Navin K. Kapur, MD; Mamas A. Mamas, MD; Christopher M. Bianco, DO

J Am Heart Assoc. 2021;10:e021808.



IHM, invasive hemodynamic monitoring

J Am Heart Assoc. 2021;10:e021808.

Baseline Characteristics of Patients Included in the Analysis Before and After Propensity Score Matching

Variables (%)	Unmatched Cohorts				Matched Cohorts			
	IHM (n=62 565)	No IHM (n=332 070)	Total (n=394 635)	SMD	IHM (n=62 220)	No IHM (n=62 220)	Total (n=12 440)	SMD
Age, median (25th–75th IQR), y	64 (55–72)	68 (58–78)	67 (58–77)	−0.24	64 (55–73)	64 (56–75)	64 (55–74)	<0.01
Female	33.1	38.6	37.7	−0.12	33.1	32.5	32.8	<0.01
Race								<0.01
White	62	65.3	64.8		62	62.7	62.4	<0.01
Black	14.9	17.7	15.3	0.04	17.7	16.2	16.9	<0.01
Hispanic	8.4	8.8	8.7		8..4	9.4	8.9	<0.01
Other*	11	11.9	11.1		11.8	11.8	11.8	<0.01
Diabetes mellitus	40.3	39.3	39.5	0.02	40.3	40.8	40.5	<0.01
Hypertension	74.4	73.6	73.7	0.02	74.4	75	74.7	<0.01
Peripheral vascular disease	12.6	12.9	12.9	−0.03	12.6	12.4	12.5	<0.01
Chronic heart failure	36.3	27.9	29.3	0.18	36	35.7	35.9	<0.01
Chronic kidney disease	39.2	36.8	37.2	0.07	39.1	38.4	38.7	<0.01
Metastatic cancer	1	2.3	2.1	−0.14	1	1.1	1	<0.01
Coagulopathy	25.5	22.7	23.1	0.07	25.4	25.7	25.6	<0.01
Chronic liver disease	6.5	6.5	6.5	<0.01	6.4	6.1	6.3	<0.01
Chronic lung disease	24.2	27.6	27.1	−0.09	24.3	24.9	24.6	<0.01
Obesity	19.4	17.7	17.9	0.04	19.4	19.9	19.6	−0.02
Prior stroke	8.3	9.2	9	−0.03	8.3	8.1	8.2	0.01
Smoking	15.2	16.5	16.3	−0.05	15.2	15.1	15.2	<0.01
STEMI	19.8	20.2	20.1	−0.04	19.9	20.3	20.1	−0.02
NSTEMI	21.9	22.5	22.4	−0.05	21.9	22.2	22	−0.01
Mechanical ventilation	39.7	49.1	47.6	−0.21	39.9	39.8	39.8	0.02
PCI	23.9	18.6	19.5	0.1	23.8	24	23.9	−0.01
ECMO	3.7	2	2.2	0.09	3.6	3.5	3.5	<0.01
Impella®	17.3	15.2	15.5	0.06	17.2	18	17.6	<0.01
IABP	23.7	11.6	13.5	0.27	23.3	22.7	23	<0.01
Hospital bed size								
Small	7.2	13.9	12.9	0.37	7.2	6.5	6.9	<0.01
Medium	18.8	27.1	25.8		18.9	19.9	19.4	
Large	74	59	61.4		73.9	73.6	73.7	
Hospital teaching status								
Rural non-teaching	1.9	4.5	4.1	0.39	7.2	6.5	6.9	0.03
Urban non-teaching	10.6	20.5	18.9		18.9	19.9	19.4	
Urban teaching	87.5	75	77		73.9	73.6	73.7	

J Am Heart Assoc. 2021;10:e021808.

In-Hospital Outcomes of Patients Included in the Analysis Before and After Propensity Score Matching

Variables no. (%)	Unmatched cohorts				Matched cohorts			
	62,565 IHM	362,070 No-IHM	Total (n=394 635)	P value	62,220 IHM	62,220 No-IHM	Total (n=12 440)	P value
In-hospital outcomes								
Death	24.1	35.8 ↑	34	<0.01	24.1	30.6 ↑	27.4	<0.01
Vascular Complication	0.9 ↑	0.7	0.7	0.01	0.9	0.9	0.9	0.89
Major bleeding	4.9	4.9	4.9	0.77	4.8	5.4	5.1	0.06
RRT	9.4 ↑	8.7	8.8	0.02	9.4	9	9.2	0.24
Center Line Blood-stream Infection	0.6 ↑	0.4	0.4	<0.01	0.6 ↑	0.4	0.5	<0.01

renal replacement therapy

J Am Heart Assoc. 2021;10:e021808.

In-Hospital Outcomes of Patients Included in the Analysis Before and After Propensity Score Matching (no IHM vs IHM)

Variables no. (%)	Unmatched cohorts				Matched cohorts			
	62,565 IHM	362,070 No-IHM	Total (n=394 635)	P value	62,220 IHM	62,220 No-IHM	Total (n=12 440)	P value
Utilization of advanced heart failure therapy								
LVAD	4.5 ↑	0.6	1.2	<0.01	4.4 ↑	1.3	2.8	<0.01
Heart Transplantation	1.4 ↑	0.3	0.5	<0.01	1.3 ↑	0.7	1	<0.01
Resources utilization								
Length of Length Of Hospitalization	11 (6 – 19) ↑	7 (3 – 13)	7 (3 – 14)	<0.01	11 (6 – 18) ↑	7 (4 – 14)	9 (5 – 16)	<0.01
Cost of Cost median $ (25th–75th IQR)	46 553 ↑ (25 685–87 062)	28 117 (14 848–51 918)	30 607 (16 129–57 055)	<0.01	45 511 ↑ (25 809–81 470)	31 290 (16 364–58 325)	38 098 (20 579–69 981)	<0.01

renal replacement therapy

J Am Heart Assoc. 2021;10:e021808.

Result from the subgroup analysis

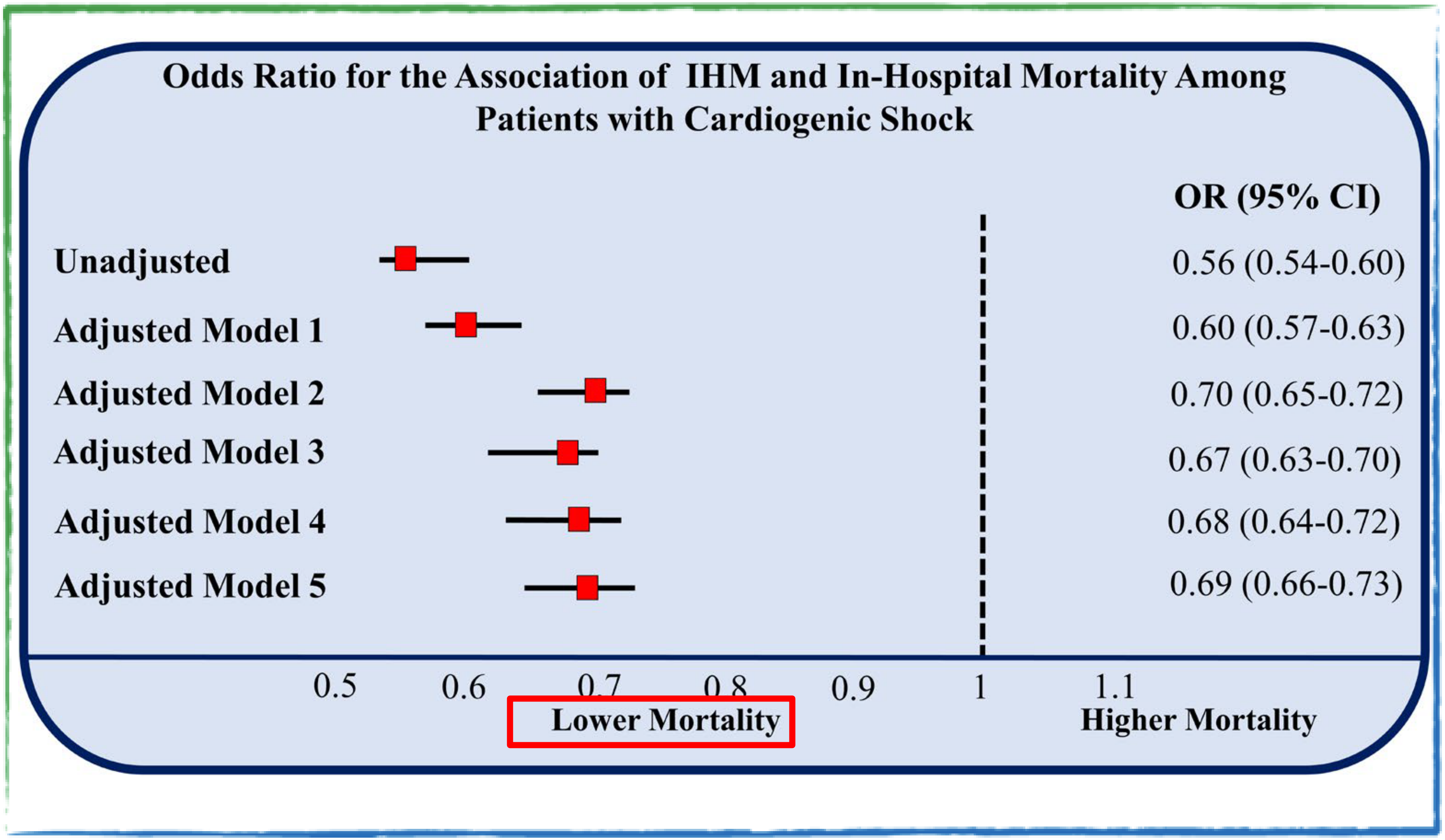
Subgroups	OR (95% CI)	p for Interaction
❖ **Sex**		
• Female	0.70 (0.64-0.77)	0.80
• Male	0.72 (0.67-0.78)	
❖ **Age (years)**		
• < 65	0.66 (0.62-0.73)	0.12
• ≥ 65	0.75 (0.70-0.81)	
❖ **Race**		
• Caucasians	0.75 (0.69-0.80)	0.64
• Non-caucasians	0.67 (0.60-0.74)	

Favors IHM 1 **Favors No IHM**

IHM indicates invasive hemodynamic monitoring; and OR, odds ratio.

J Am Heart Assoc. 2021;10:e021808.

Results of the multivariable risk adjustment analysis



IHM indicates invasive hemodynamic monitoring; and OR, odds ratio.

J Am Heart Assoc. 2021;10:e021808.

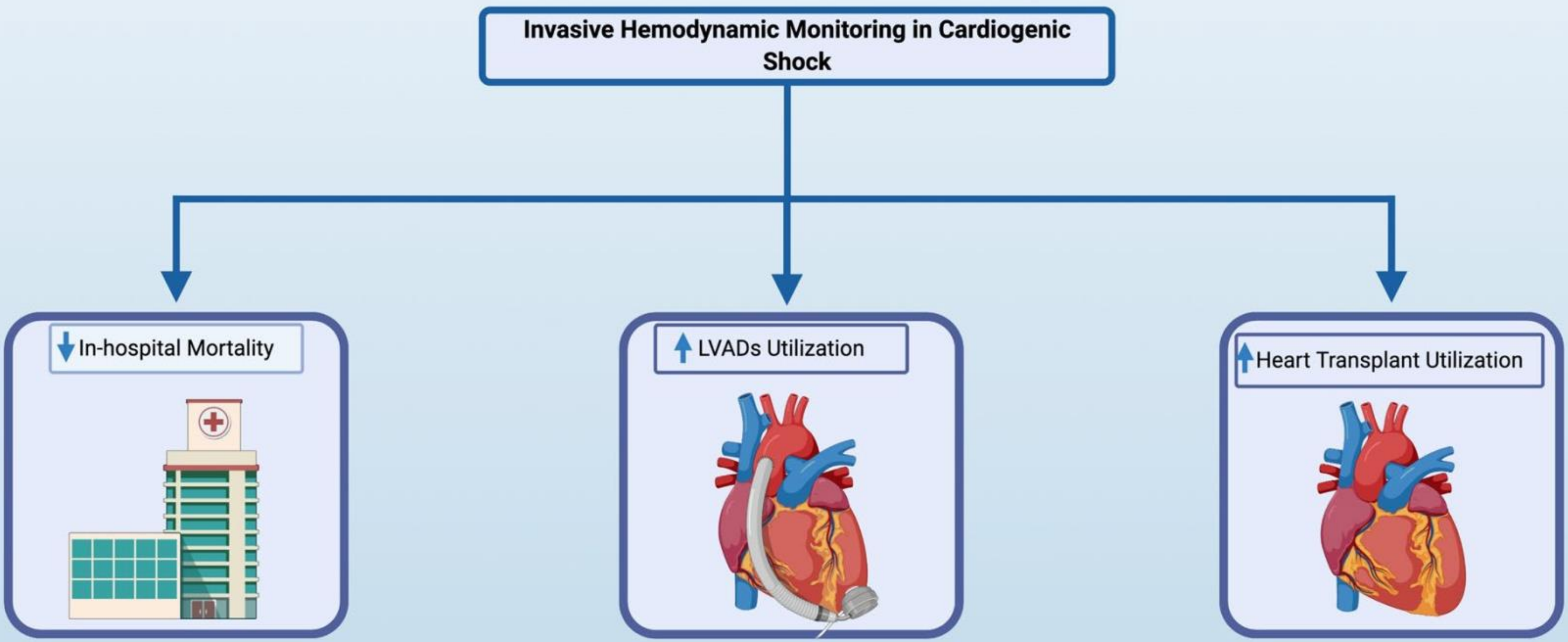
In-Hospital Outcomes Based on Timing of IHM of the Patients Included in Analysis Before and After Propensity Score Matching
Late IHM (24 Hr -1 Wk) vs No-IHM

	Unmatched cohorts				Matched cohorts			
	21,145 Late IHM	362,070 No-IHM	Total (n=353 215)	P Value	21,025 Late IHM	21,025 No-IHM	Total (n=42 050)	P Value
Death	22	35	34.5	<0.01	21.5	29	25.3	<0.01
RRT	9.3	8.9	8.9	0.34	9.3	10	9.6	0.28
Heart Transplatation	1.3	0.5	0.5	<0.01	1.2	1.3	1.2	0.63
LVAD	5.2	0.8	1.1	<0.01	5.1	2.3	3.7	<0.01

IHM indicates invasive hemodynamic monitoring; LVAD, left ventricular assist devices; and RRT, renal replacement therapy.

J Am Heart Assoc. 2021;10:e021808.

Invasive Hemodynamic Monitoring in Cardiogenic Shock



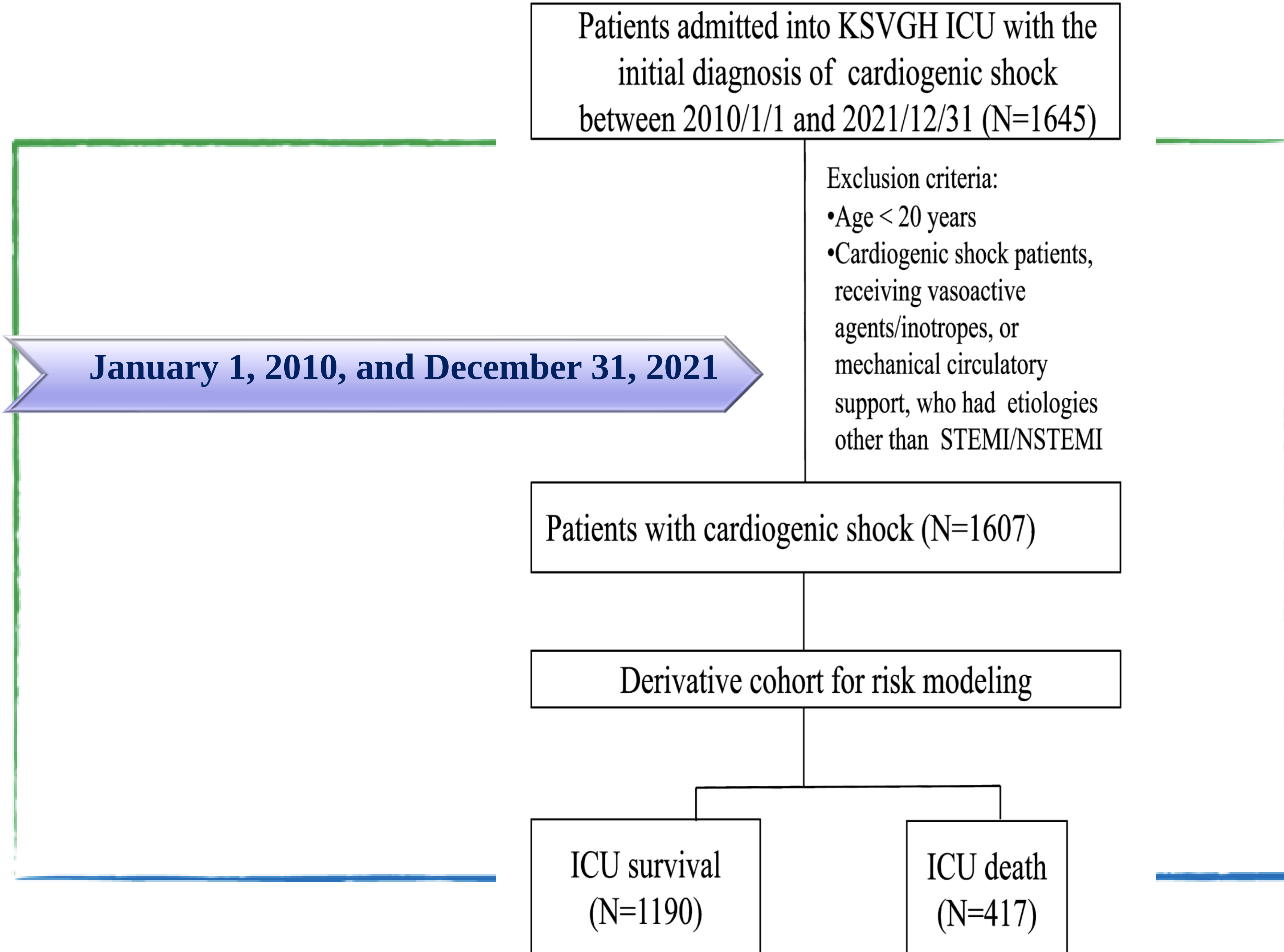
In-hospital Mortality

LVADs Use

Heart Transplantation

J Am Heart Assoc. 2021;10:e021808.

KSVGH Artificial Intelligence Care in Cardiogenic Shock


January 1, 2010, and December 31, 2021
Patients admitted into KSVGH ICU with the initial diagnosis of cardiogenic shock between 2010/1/1 and 2021/12/31 (N=1645)
Exclusion criteria:
•Age < 20 years
•Cardiogenic shock patients, receiving vasoactive agents/inotropes, or mechanical circulatory support, who had etiologies other than STEMI/NSTEMI
Patients with cardiogenic shock (N=1607)
Derivative cohort for risk modeling
ICU survival (N=1190)
ICU death (N=417)

The first reported clinical data after admission

Variables	Beta	Adjusted odds ratio (95% CI)	P-value	Points
65-75 years	0.662	1.94 (1.14–3.21)	0.014	2
>75 years	0.599	1.82 (1.08–3.08)	0.025	2
Female	0.578	1.78 (1.03–3.09)	0.039	2
APACHE II >20	0.706	2.03 (1.30–3.16)	0.002	2
Body weight >65 kg	0.176	1.19 (0.77–1.86)	0.437	1
Body height >160 cm	0.023	1.02 (0.60–1.74)	0.932	1
Heart rate>100 bpm	0.643	1.90 (1.25–2.91)	0.003	2
Neutrophil>75%	0.439	1.55 (1.01–2.38)	0.043	1
Blood urea nitrogen >35 mg/dL	0.319	1.38 (0.78–2.43)	0.270	1
Serum creatinine >2 mg/dL	0.058	1.06 (0.77–1.46)	0.723	1
Aspartate aminotransferase >200 U/L	0.506	1.66 (1.04–2.65)	0.034	1
Hypertension	-0.198	0.82 (0.50–1.35)	0.433	-1
Diabetes mellitus	-0.462	0.63 (0.39–1.03)	0.064	-1
Hyperlipidemia	-0.588	0.56 (0.33–0.94)	0.028	-2
Chronic kidney disease	-0.532	0.59 (0.32–1.09)	0.091	-1
Platelet >214 K/uL	-0.225	0.80 (0.53–1.21)	0.284	-1

Basic

APACHE

Vital Sign

Etiology

Comorbidities

Device

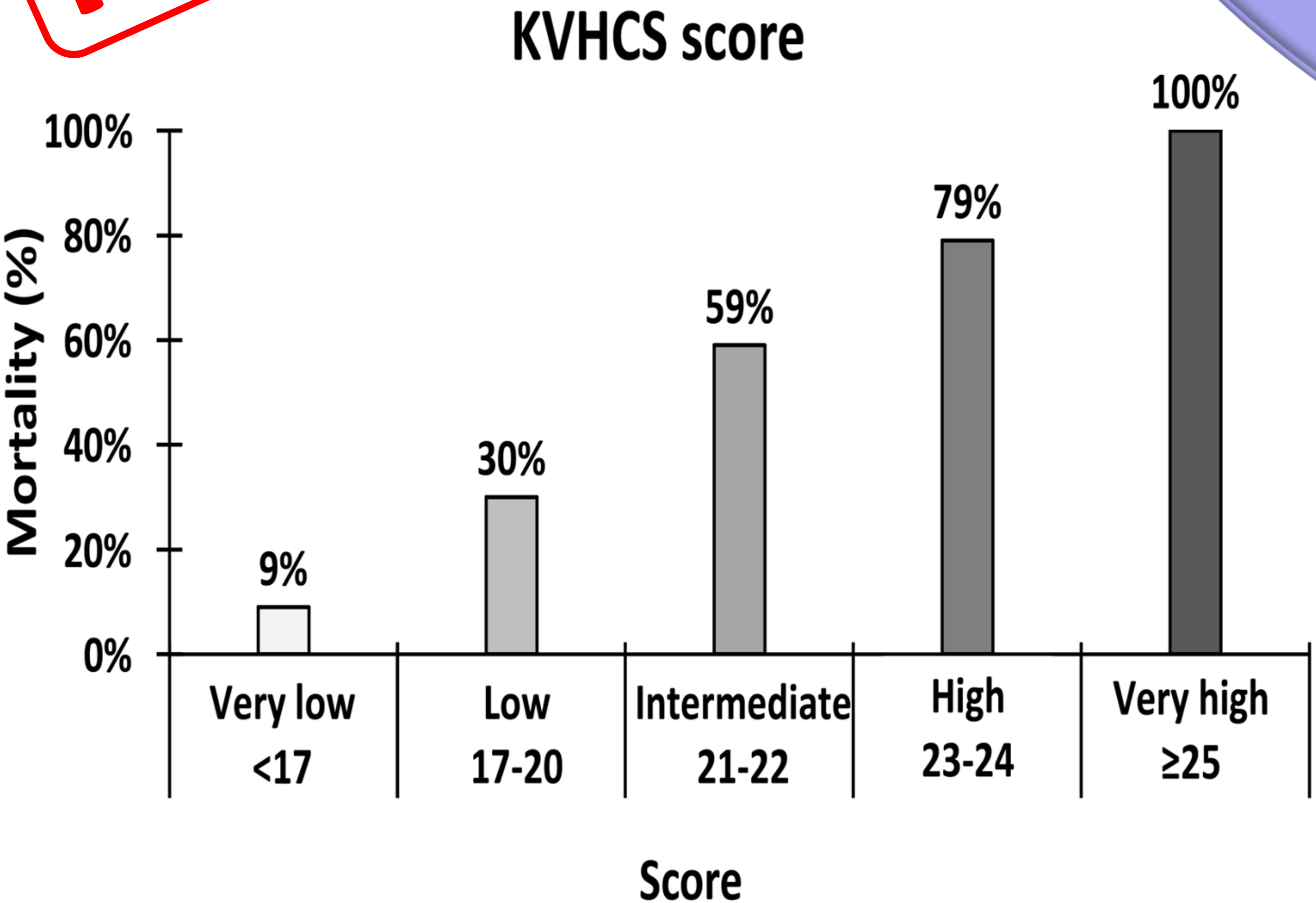
Lab

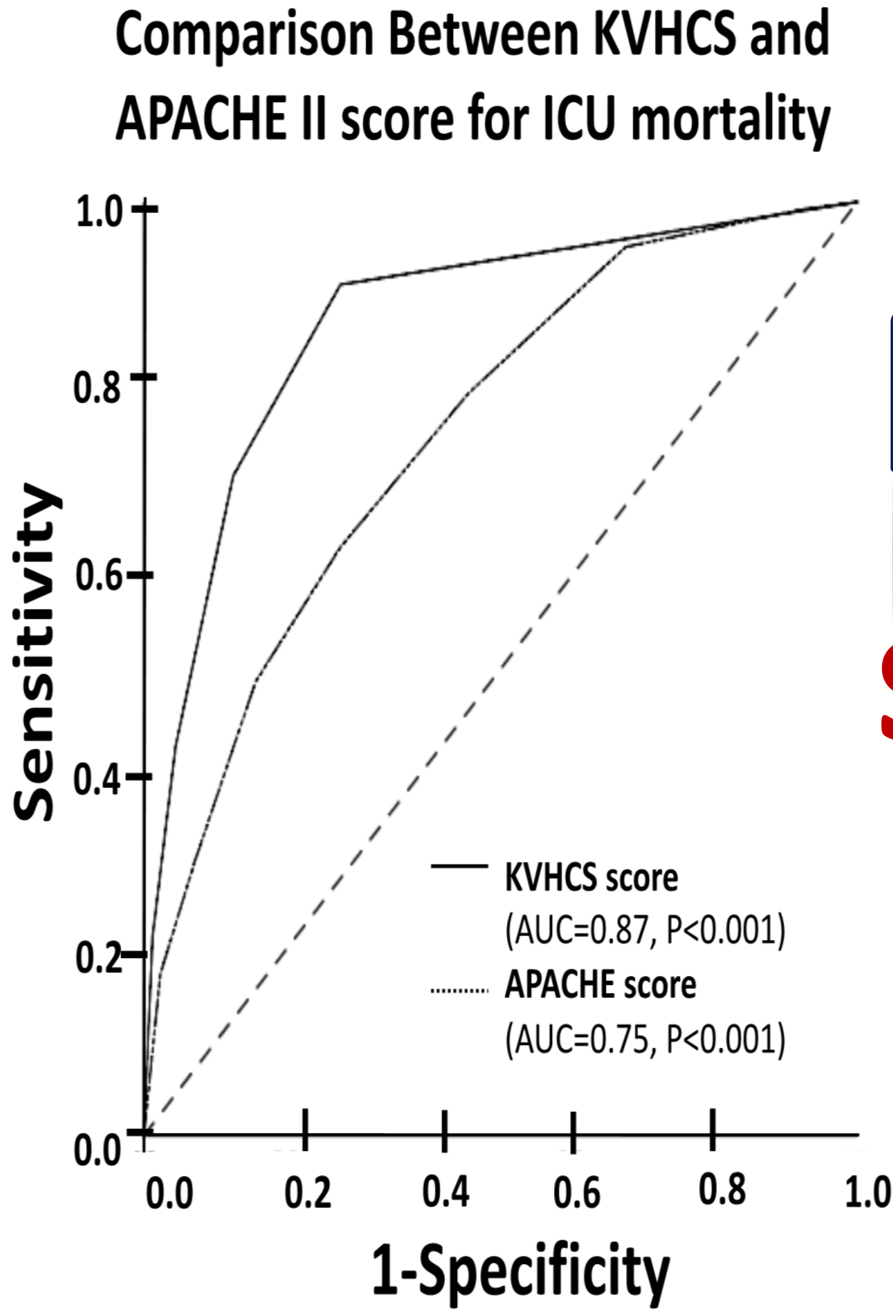
Variables	Points
65-75 years	2
>75 years	2
Female	2
APACHE II >20	2
Body weight >65 kg	1
Body height >160 cm	1
Heart rate>100 bpm	2
NSTEMI (N, %)	0
STEMI (N, %)	0
Coronary artery disease	10
Congestive heart failure	1
Ventilator use	2
Neutrophil>75%	1
Blood urea nitrogen >35 mg/dL	1
Serum creatinine >2 mg/dL	1
Aspartate aminotransferase >200 U/L	1
Hypertension	-1
Diabetes mellitus	-1
Hyperlipidemia	-2
Chronic kidney disease	-1
Platelet >214 K/uL	-1

Precise

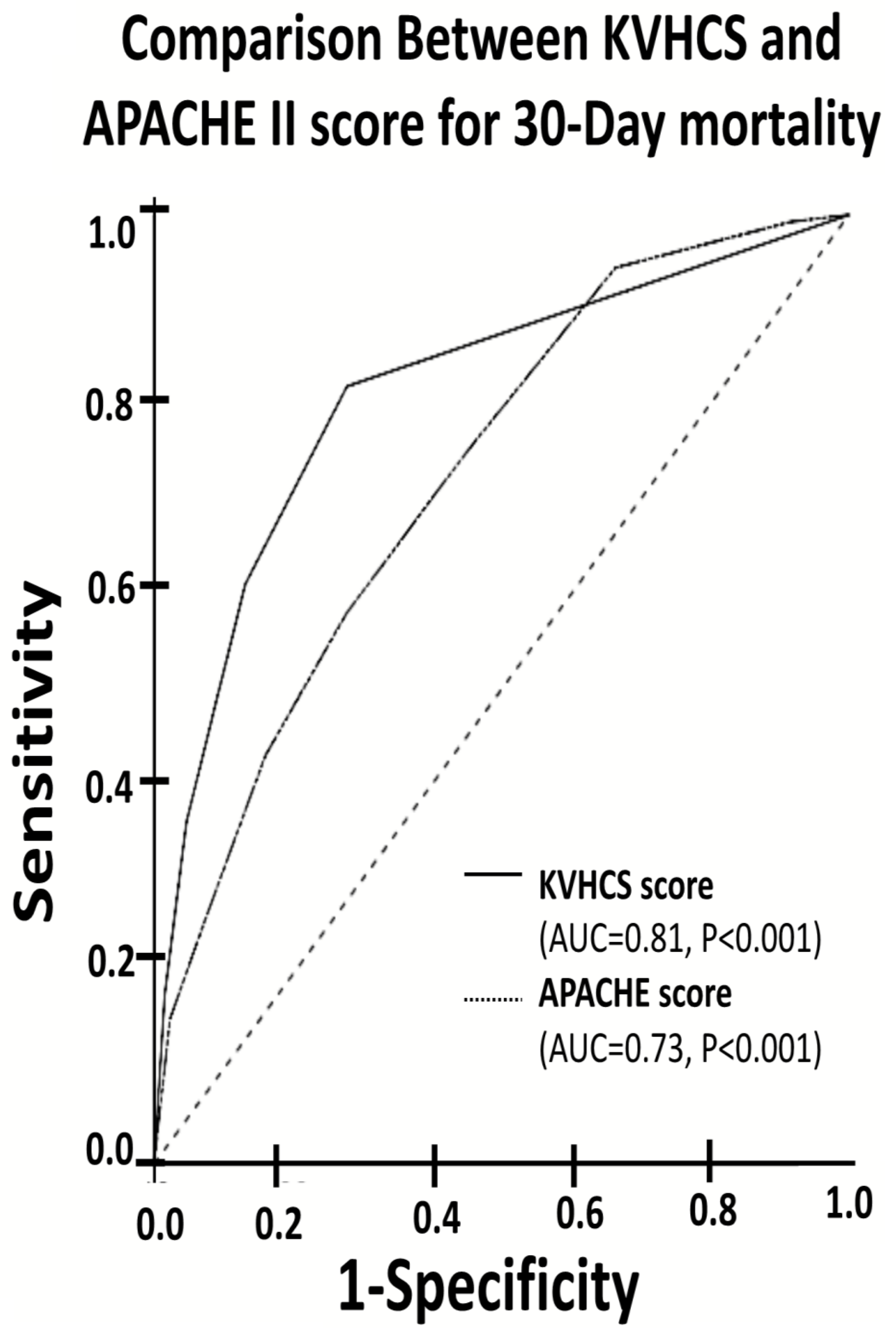
KVHCS

5-Strata





Powerful
short-term



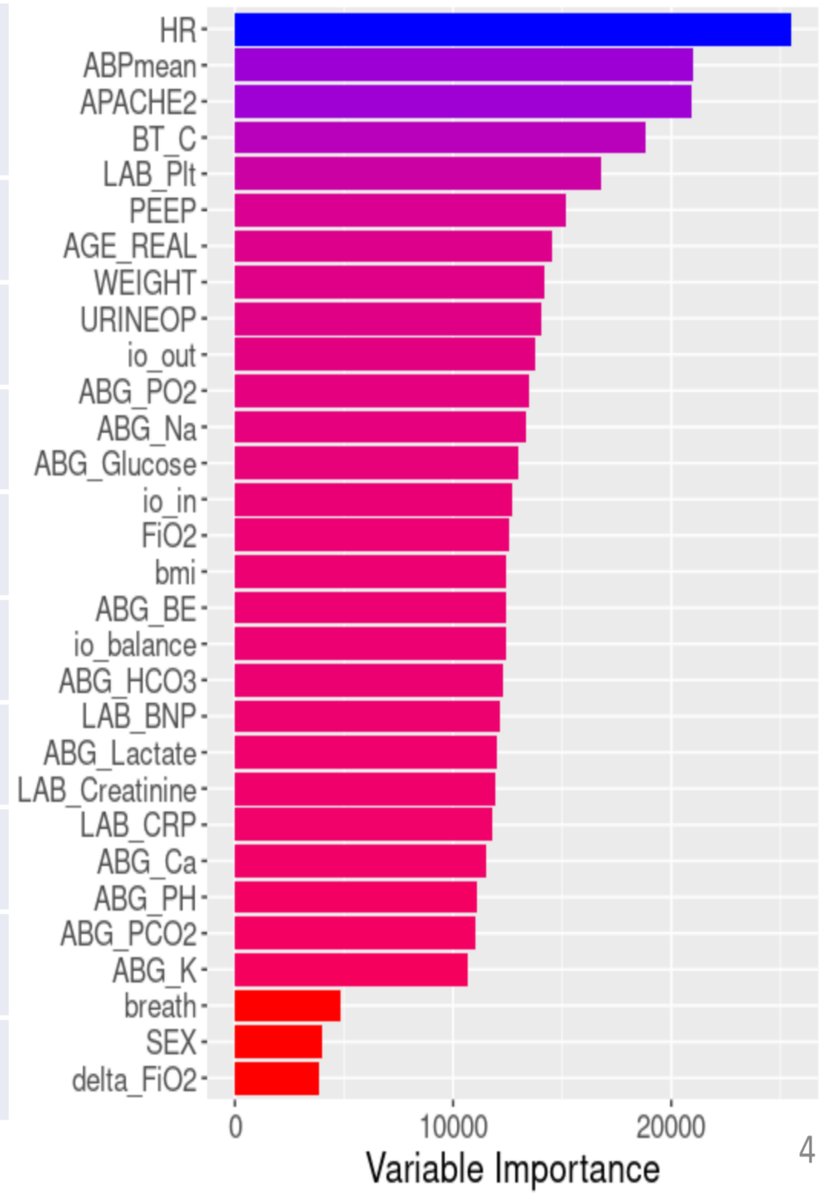
Powerful

long-term

Random Forest and Variable Importance

Hyper-Parameters		500 trees, 30 Vars
Cross Entropy	Train	0.1641
	Valid	0.2110
	Test	0.2034
AUROC	Train	0.9658
	Valid	0.9046
	Test	0.7353
AUPRC	Train	0.0007
	Valid	0.0077
	Test	0.0050

Random Forest



4

SHAP Explanation on Random Forest Prediction

	origin_id	prob
1	19848	0.664712688
2	23432	0.701682498
3	23433	0.691780667
4	23434	0.676885432
5	23449	0.653779395
6	33977	0.664368938
7	33978	0.674831526
8	159364	0.676088540
9	159365	0.683950982
10	159366	0.654659548
11	9178	0.004904674

Comparing SHAP explanation between 2 high-risk patients

Comparing SHAP explanation between high-risk and low-risk patients

Conclusion 1/2

- Hemodynamic monitoring is critical in CHIP PCI and CS
  - Important for diagnosis of cardiogenic shock.
  - Acute management of patients receiving therapy with MCS.
  - To guide withdrawal of mechanical circulatory and pharmacologic support in patients with myocardial recovery from cardiogenic shock.
  - Increase transplatation

Conclusion 2/2

- Routine use of invasive hemodynamic monitoring
  - NOT recommended in normotensive patients with acute decompensated HF and congestion with symptomatic response to diuretics and vasodilators
- Adequate invasive Hemodynamic Mentoring in CS
  - Reduce in-hospital mortality
  - Increase LVAD use
  - Increase transplatation

黃偉春

wchuanglulu@gmail.com

Saving Heartbeat of the world

Prof. Wei-Chun Huang, MD, PhD, FACC, FESC

黃偉春主任
Dr. Wei-Chun Huang , MD, PhD, FESC, FACC, FHQS

- 美國心臟學院院士 FACC
- 歐洲心臟學會院士 FESC
- Stent Save a Life 心肌梗塞國際組織 台灣代表
- 國際健康照護品質協會 ISQUa 品質專家 FHQS
- 亞洲緊急心導管治療大會APAC 主席團Course Director
- APAC Handbook of Primary PCI 編輯會議 編輯委員
- 美國心臟學會ACC 心臟衰竭教育計畫編輯委員
- 亞洲復甦醫學聯合會 RCA冠心病 Task Force委員
- 英國領導管理學會ILM（Institute of Leadership and Management）國際企業管理師證照

血行動力學

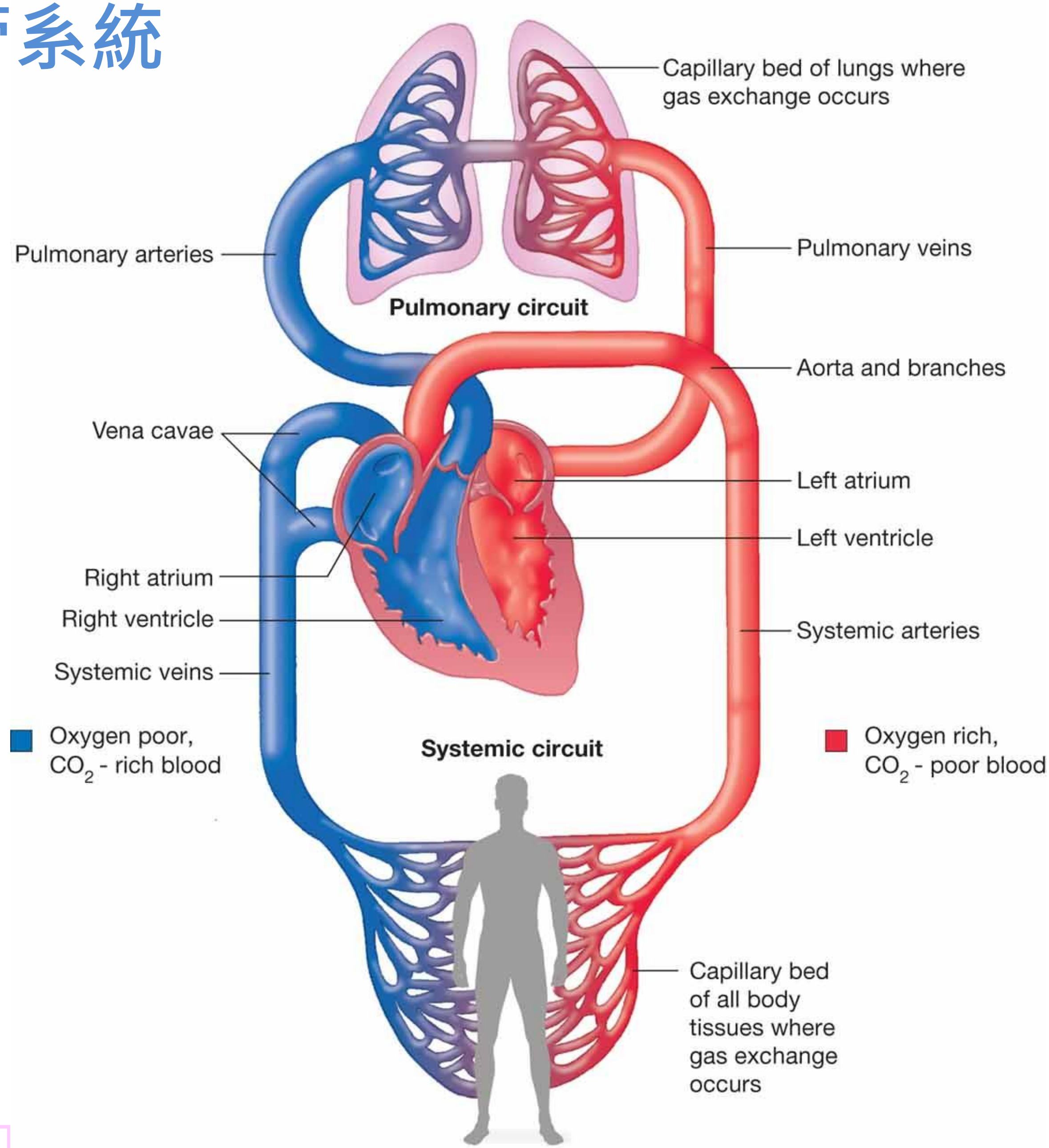
- Cardiovascular physiology dealing with the **forces** the pump (the heart) has to develop to **circulate blood** through the cardiovascular system.
- Adequate blood circulation (blood flow) is a necessary condition for **adequate supply of oxygen to all tissues**

✓ **Pressure**

✓ **Flow**

✓ **Resistance**

心血管系統

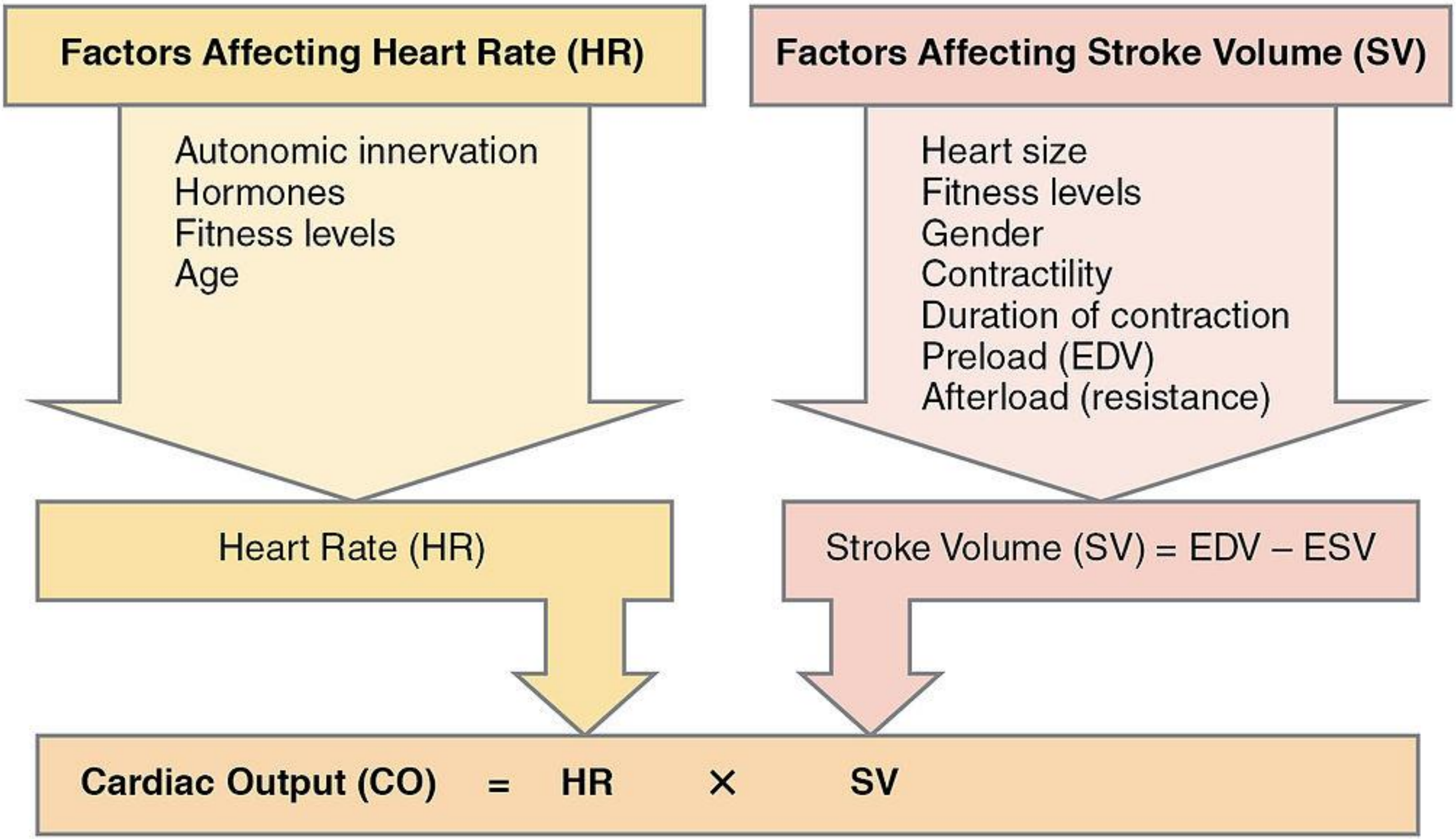


Capillary bed of lungs where gas exchange occurs
Pulmonary arteries
Pulmonary veins
Pulmonary circuit
Aorta and branches
Vena cavae
Left atrium
Left ventricle
Right atrium
Right ventricle
Systemic arteries
Systemic veins
Oxygen poor, CO_2 - rich blood
Systemic circuit
Oxygen rich, CO_2 - poor blood
Capillary bed of all body tissues where gas exchange occurs

心血管系統生理

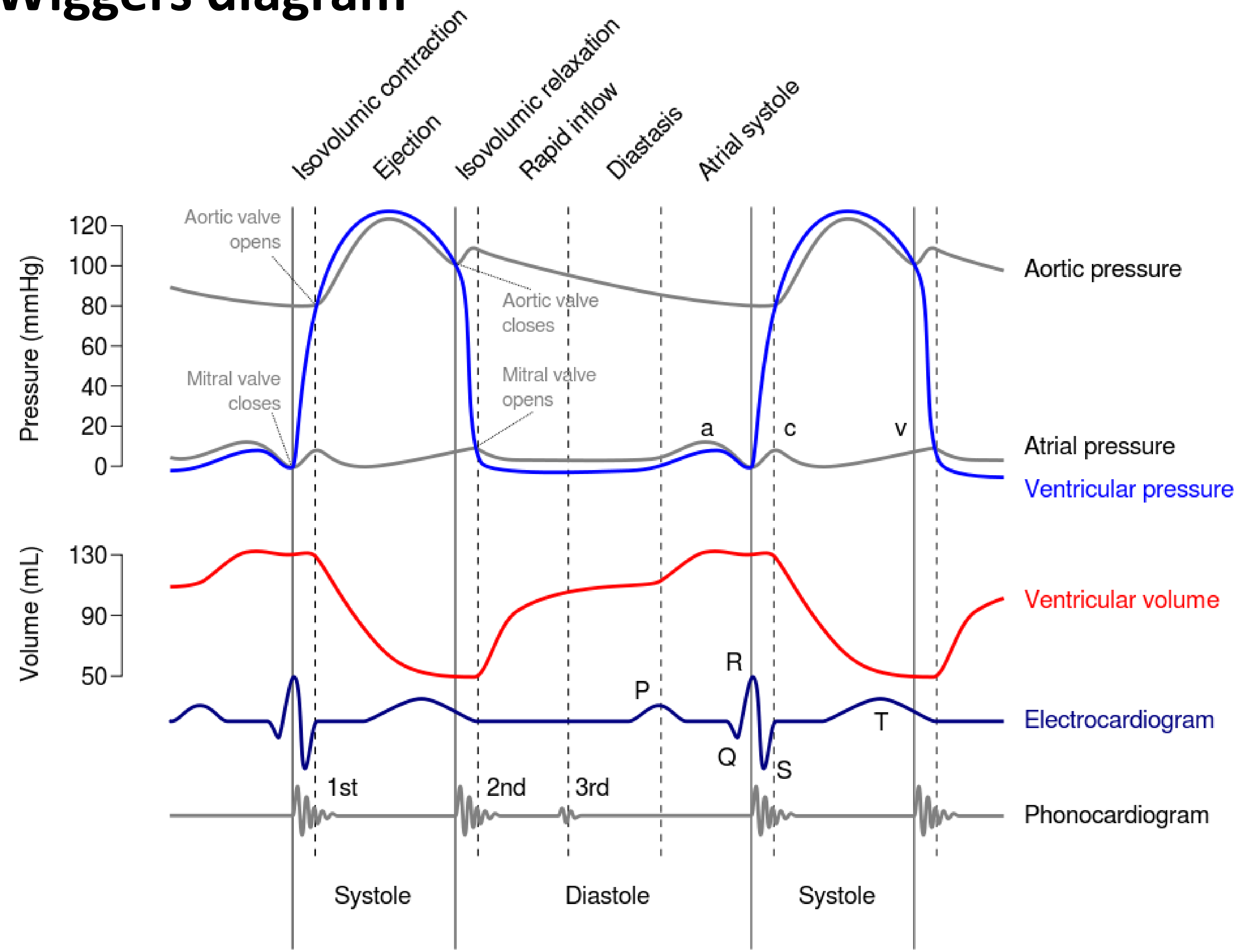
- Cardiac output = heart rate x stroke volume (L/min)
  - Stroke volume = end-diastolic volume - end-systolic volume
  - Ejection fraction = stroke volume / end-diastolic volume
- Cardiac index= $\frac{cardiac\ output}{body\ surface\ area}$ (L/min/m2)
- Maximum heart rate=220-age (years)

心輸出量調控



Factors Affecting Heart Rate (HR)
Autonomic innervation
Hormones
Fitness levels
Age
Factors Affecting Stroke Volume (SV)
Heart size
Fitness levels
Gender
Contractility
Duration of contraction
Preload (EDV)
Afterload (resistance)
Heart Rate (HR)
Stroke Volume (SV) = EDV – ESV
Cardiac Output (CO) = HR × SV

Wiggers diagram



Dr. Carl J. Wiggers.

血行動力學評估

- CVP
- A-line blood pressure
- PA catheterization
- Hemodynamic assessment in the cardiac catheterization laboratory

Hemodynamics in cath lab

- Pressure value
- Pressure contour (waveforms)
- Cardiac output
- Vascular resistance
- Oxygenation
- Shunt quantification

獲得血流動力監測正確值的步驟

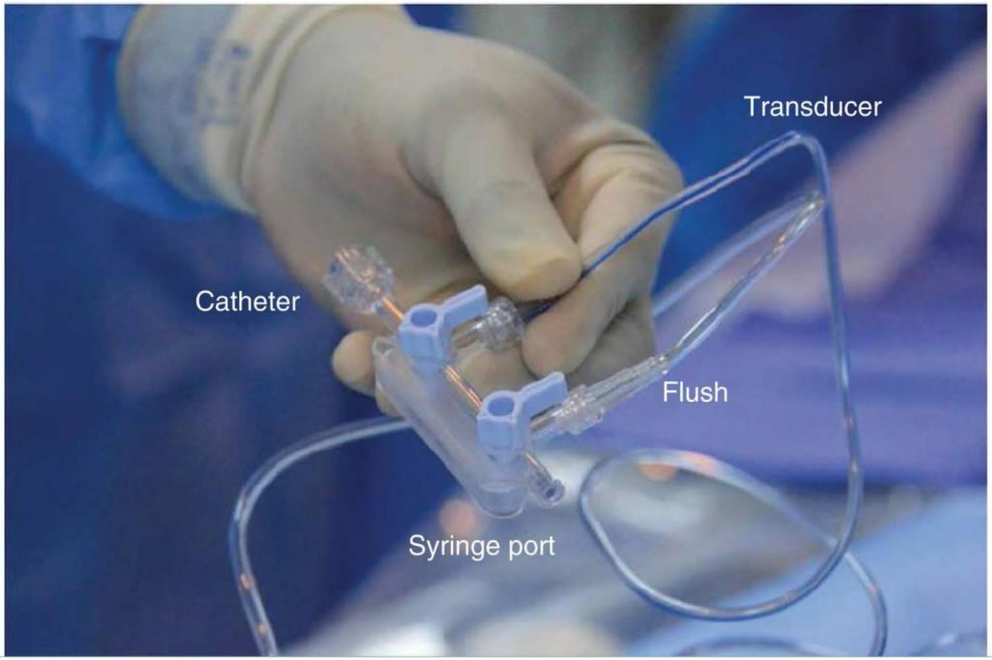
1 Labeling：正確的體外零點。

2. Zeroing：歸零。

3. Calibration：監測儀器之矯正。

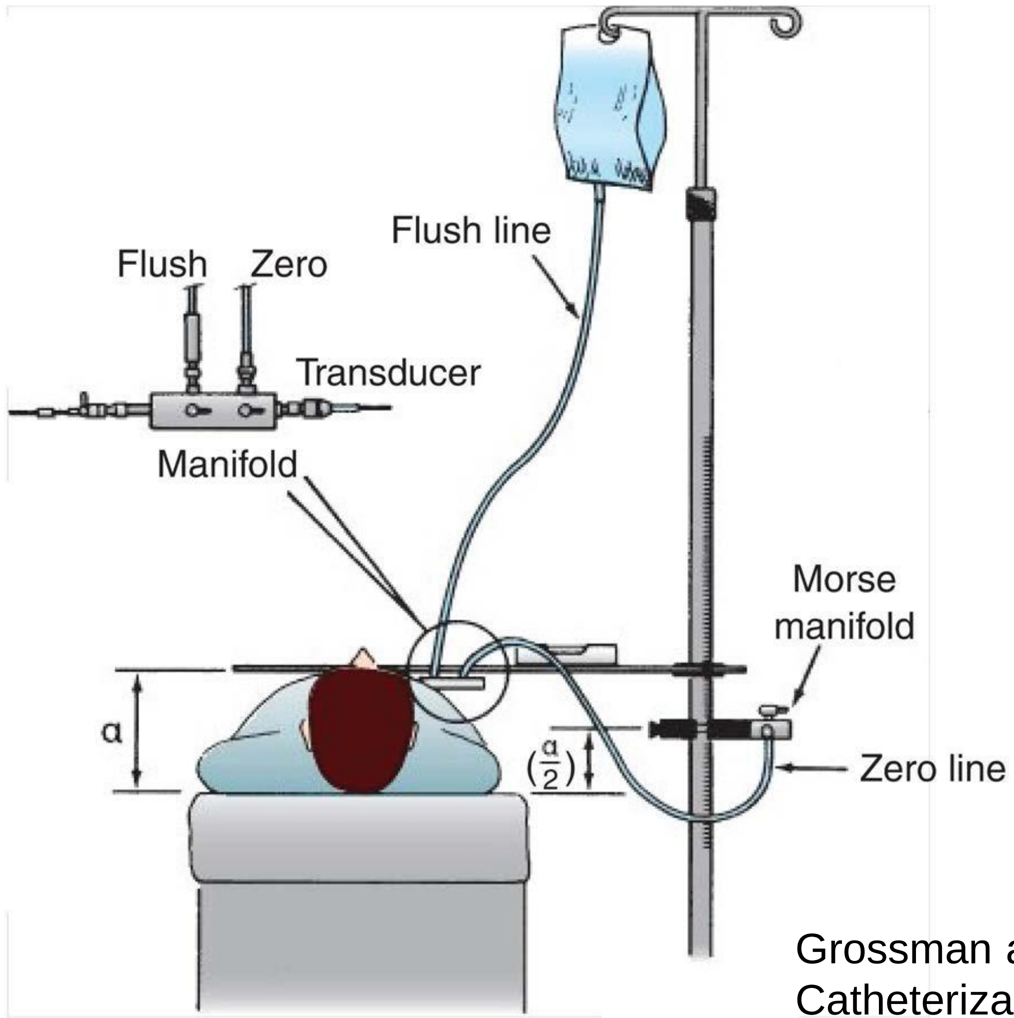
Accurate measurement

- Adequate flush catheters, avoid bubbles
- Equipment equalization
- Transducer level-zero reference line



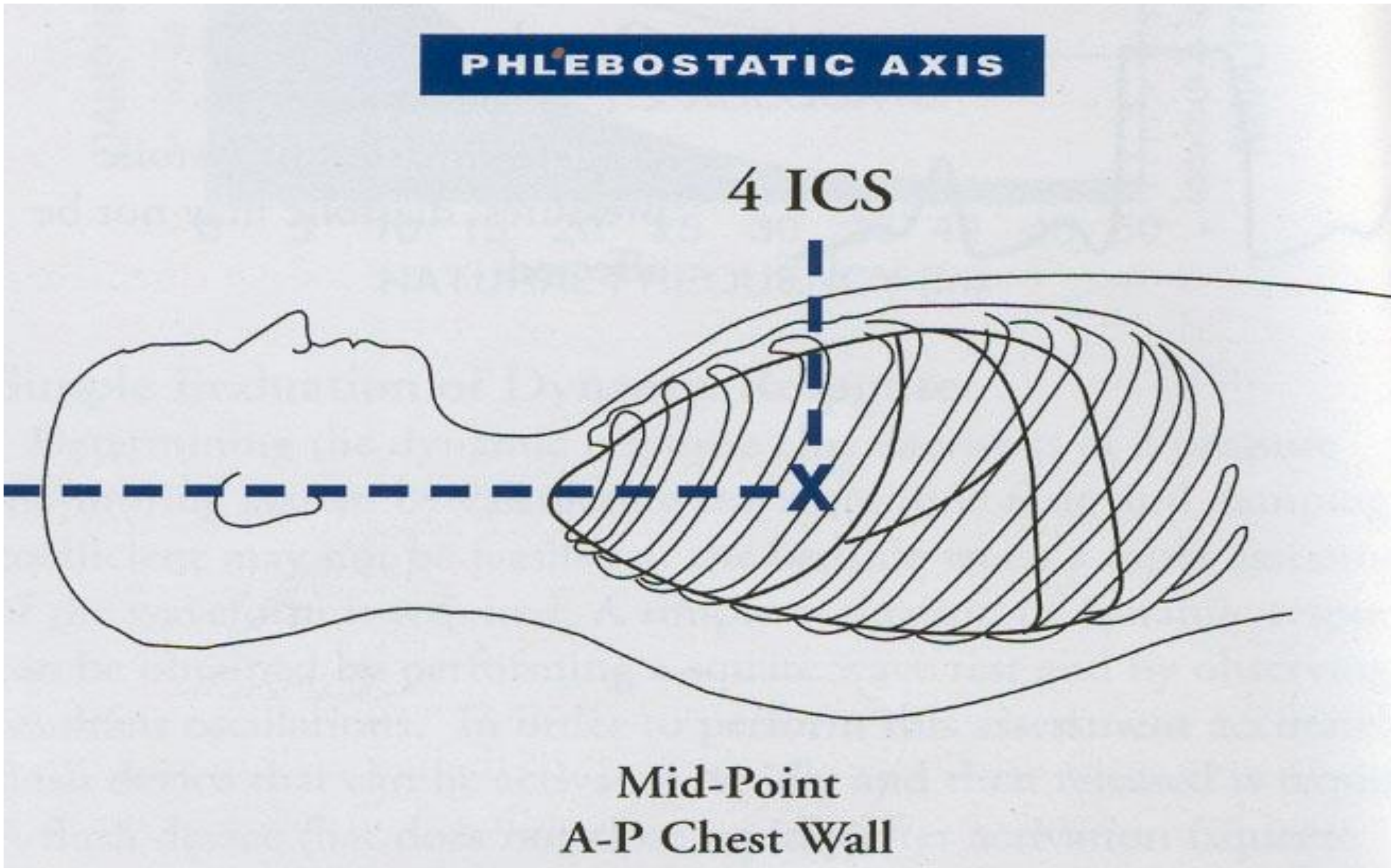
Grossman and Baim's Cardiac Catheterization, Angiography, and Intervention, 8E (2014)

Transducer level



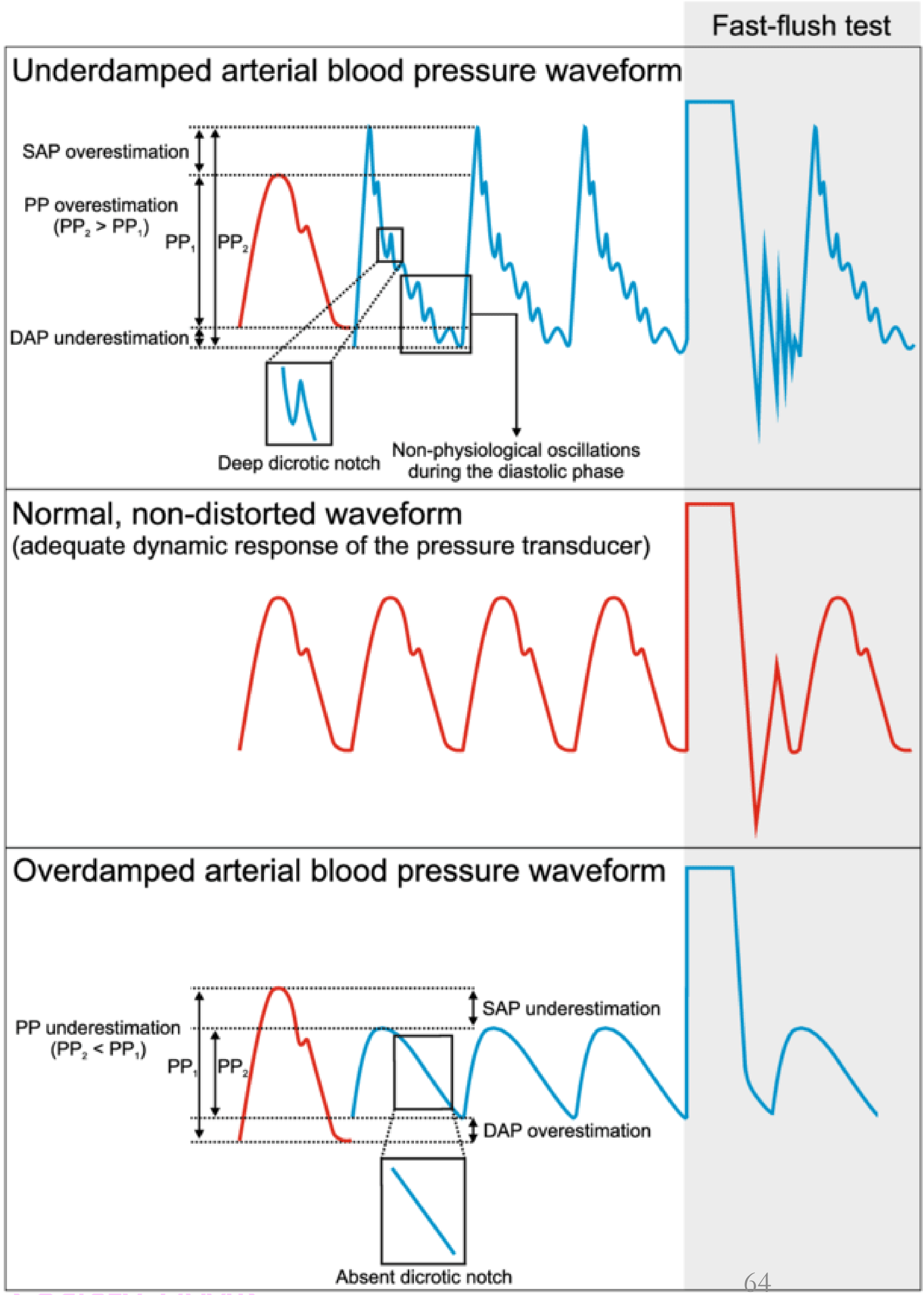
Grossman and Baim's Cardiac Catheterization, Angiography, and Intervention, 8E (2014)

正確的體外零點 － 腋中線

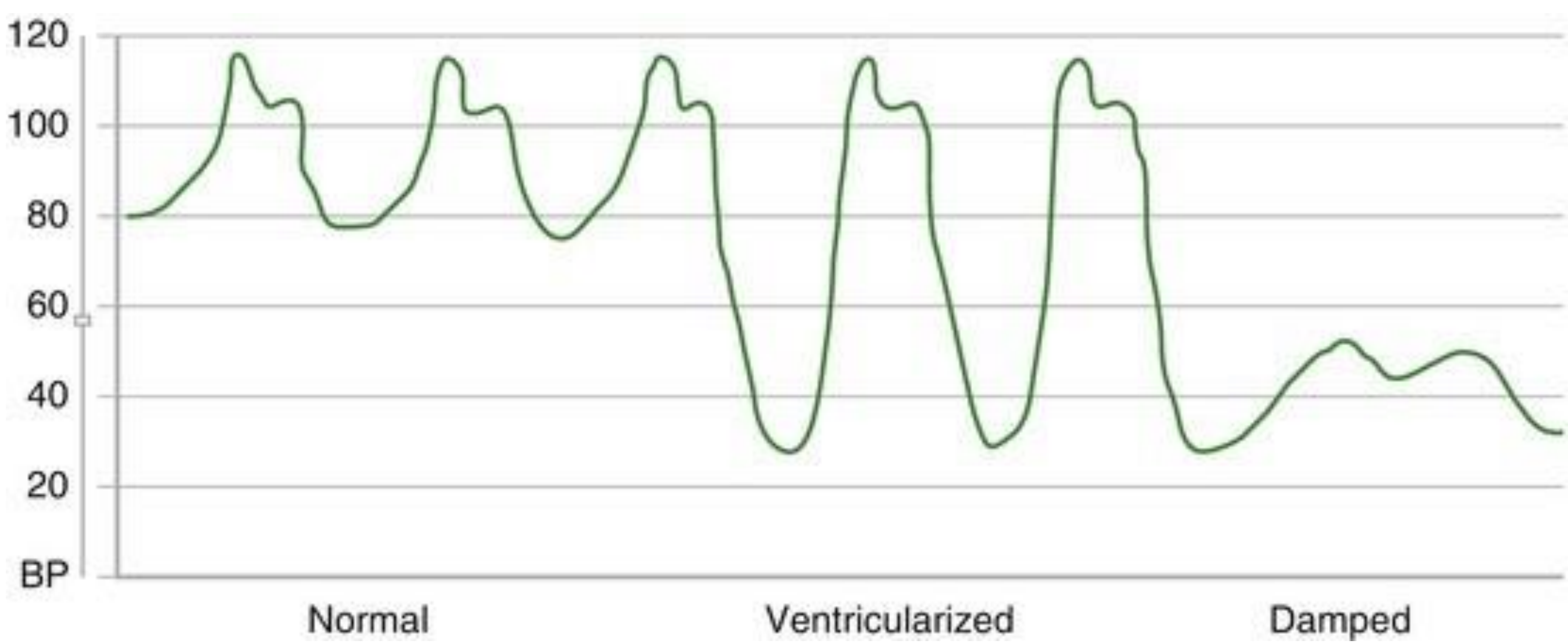


Fast flushing test
快速冲洗試驗

- Normal
- Underdamping
- Overdamping



Pressure, Damping and Ventricularization

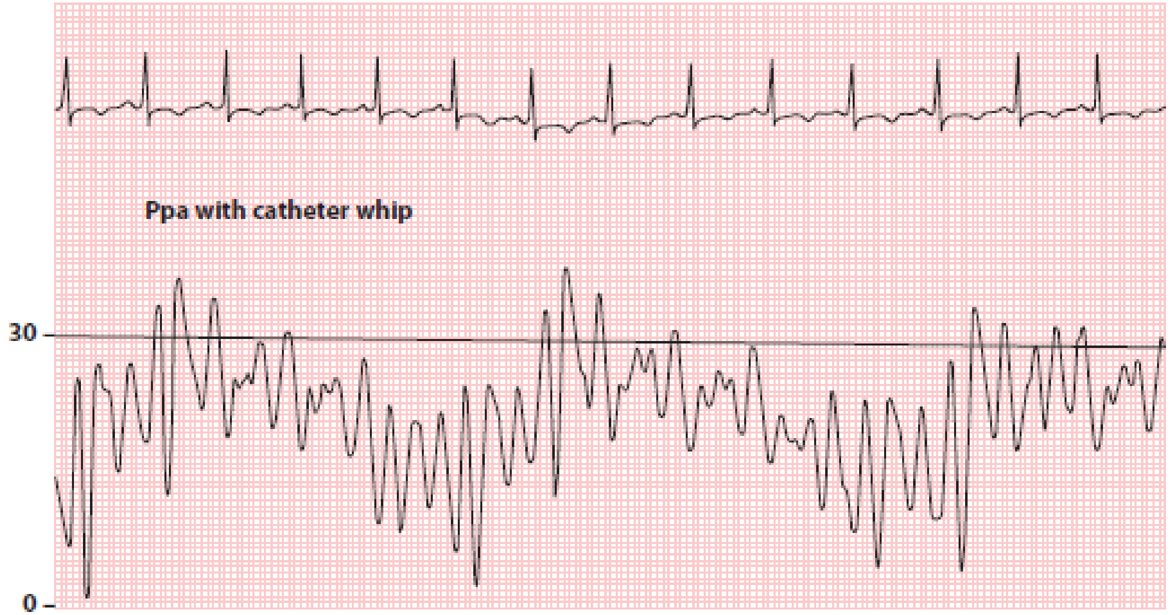


Source of error

- Tachycardia
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Catheter whip artifact

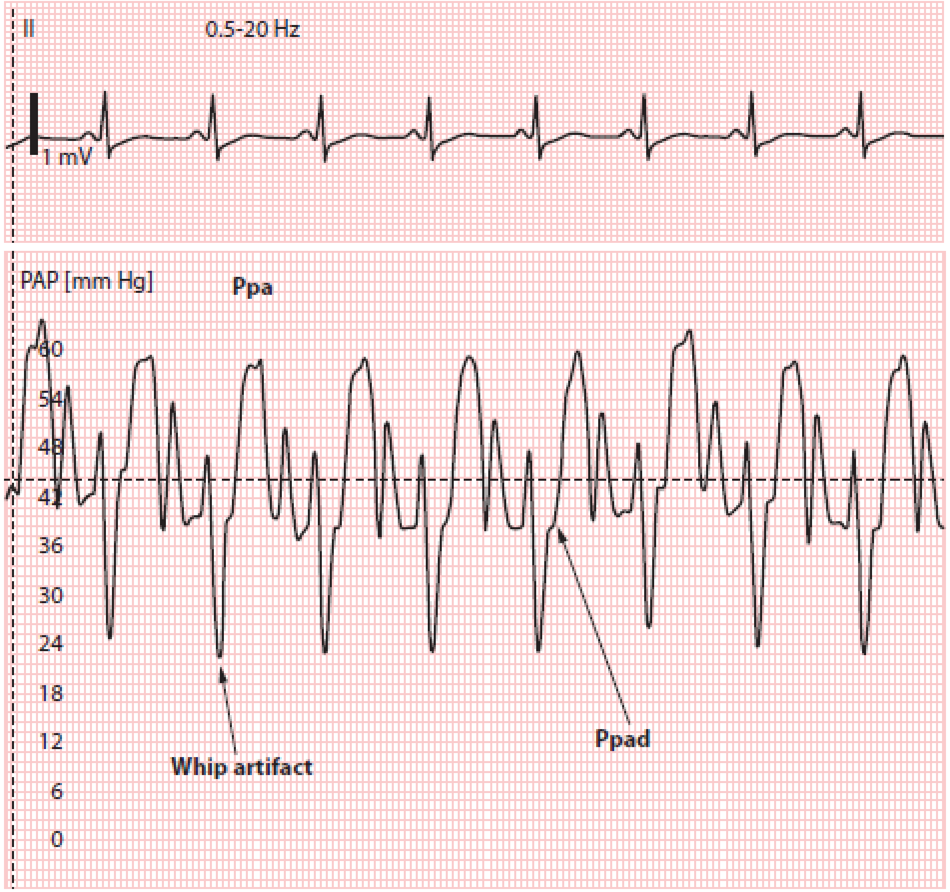
- Motion of tip of the catheter within the measured chamber
- Enhance the fluid oscillations of the transducer system



Source: Jesse B. Hall, Gregory A. Schmidt, John P. Kress: *Principles of Critical Care*, 4th Edition: www.accessmedicine.com

Catheter whip artifact

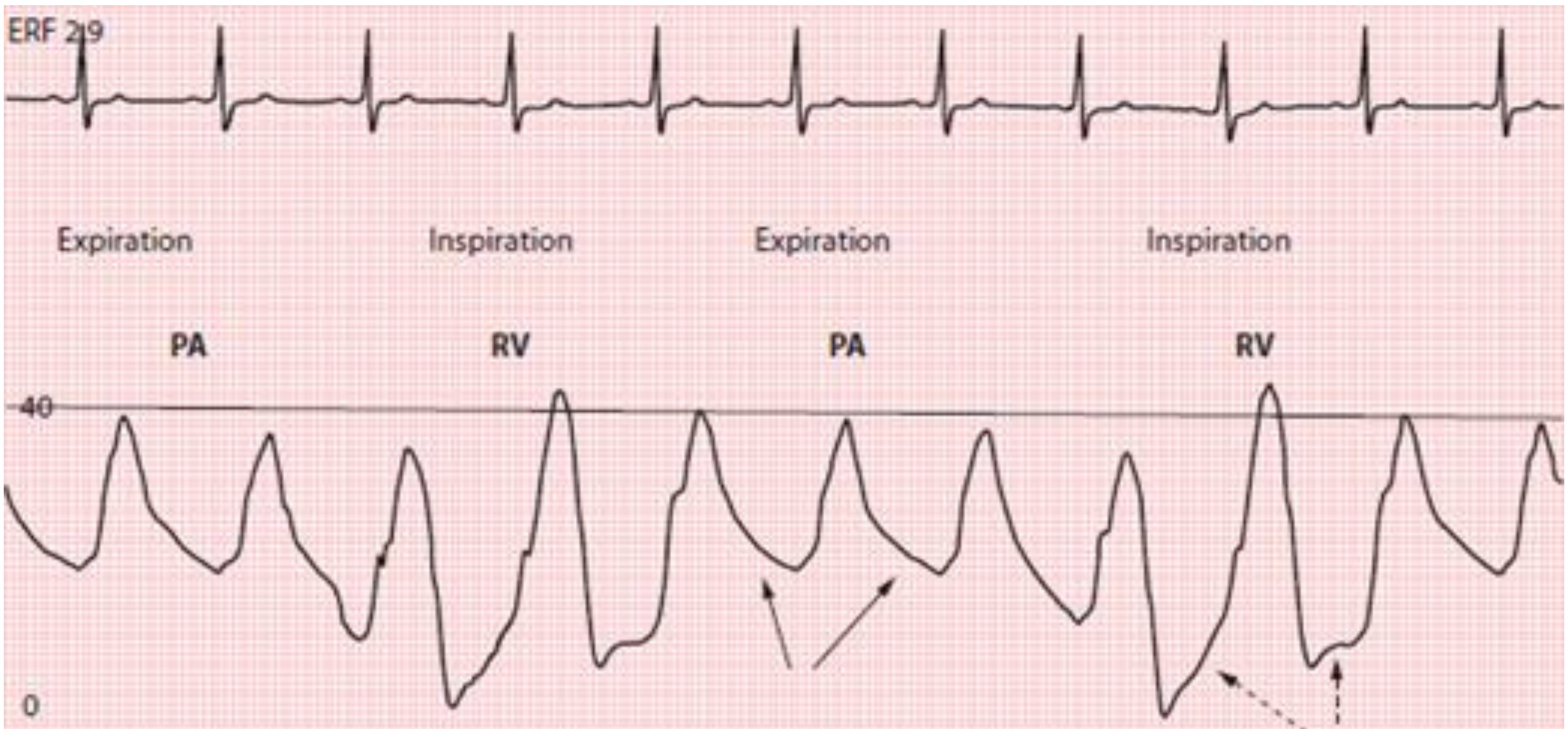
- The PADP is recorded as the pressure just before the beginning of the systolic pressure wave.
- Catheter whip artifacts can lead to significant underestimation of the PADP



Source: Jesse B. Hall, Gregory A. Schmidt, John P. Kress: *Principles of Critical Care*, 4th Edition: www.accessmedicine.com

Catheter tip positioned too proximally PA

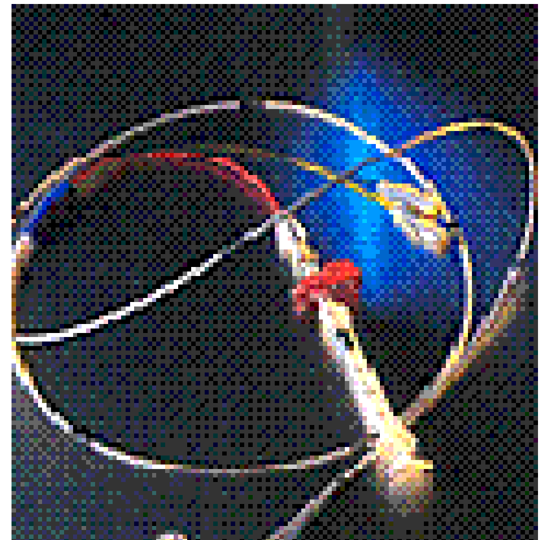
- Inspiration, the catheter tip moves back into the RV



Source: Jesse B. Hall, Gregory A. Schmidt, John P. Kress: *Principles of Critical Care*, 4th Edition: www.accessmedicine.com

Catheters for right heart catheterization

1. Wedge catheter
2. Berman catheter
3. Multi-purpose A/B
4. Swan-Ganz catheter



Difficulty in advancing S-W catheter into PA

1. Withdraw the S-W catheter into RA
2. Advance 0.025in Terumo Glide wire (keep the tip of guidewire upward)
3. Advance the S.W catheter from RA through RV into PA
   1) Initially, slightly advance with counterclockwise rotation
   2) Then, advance with clockwise rotation
   3) Sometimes, withdraw S-G catheter and inflate the balloon of S-G catheter is helpful.

Don't do ....

1. Inflate Swan-Ganz balloon in RV while using Terumo guidewire → Avoid tangle chordae of tricuspid valve
2. Inflate Swan-Ganz balloon in distal small PA → Avoid PA rupture
3. Deflate Swan-Ganz balloon while pulling back the catheter, especially crossing valves

Contraindications for RHC

1. Tricuspid mechanical valve
2. Pulmonary mechanical valve
3. Mass or thrombus in right atrium/ventricle
4. Endocarditis on tricuspid/pulmonary valve

Complications

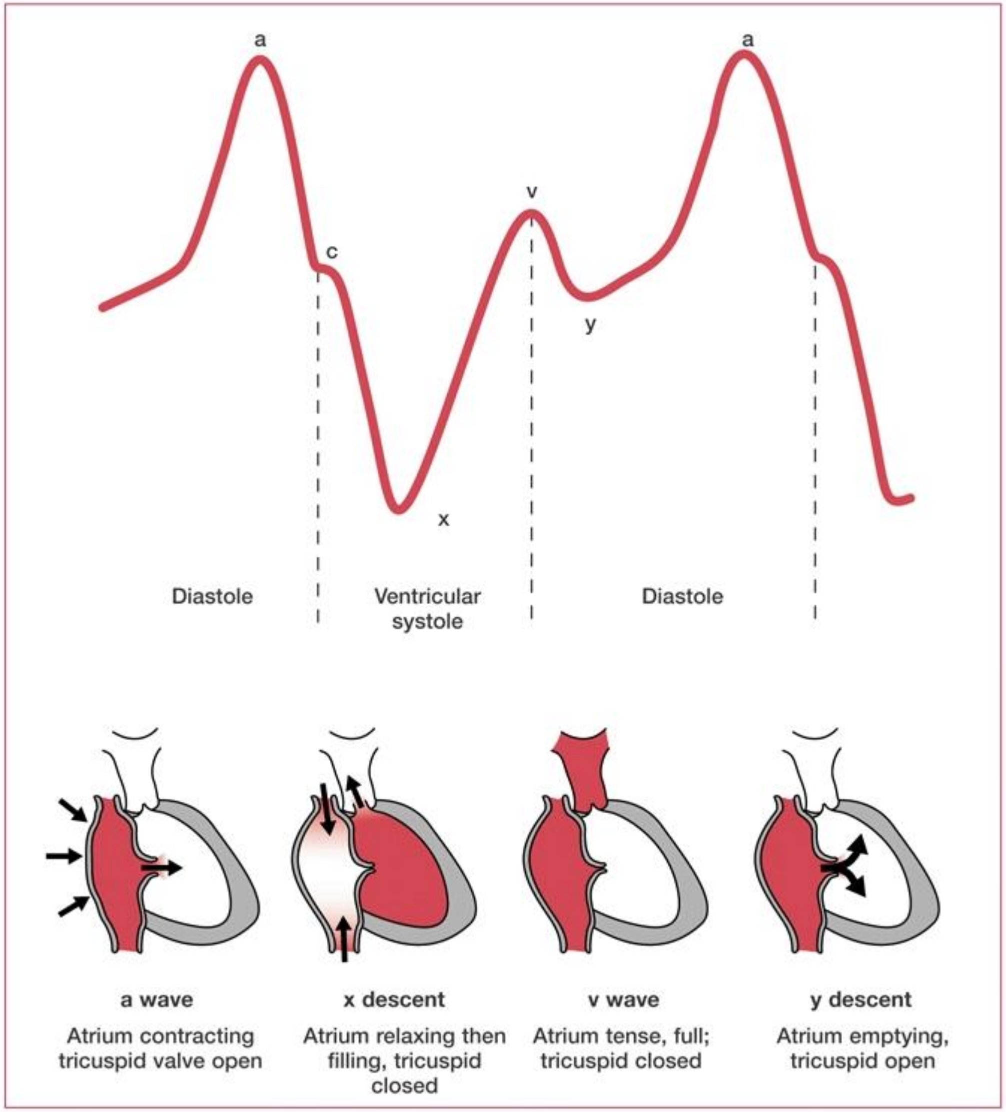
1. Access site:
   – Pneumothorax
   – Hemothorax
   – Tracheal perforation
   – Hematoma or Pseudoaneurysm
   – Arteriovenous fistula

   } **Frequent, but could be avoided by sono-guided puncture**

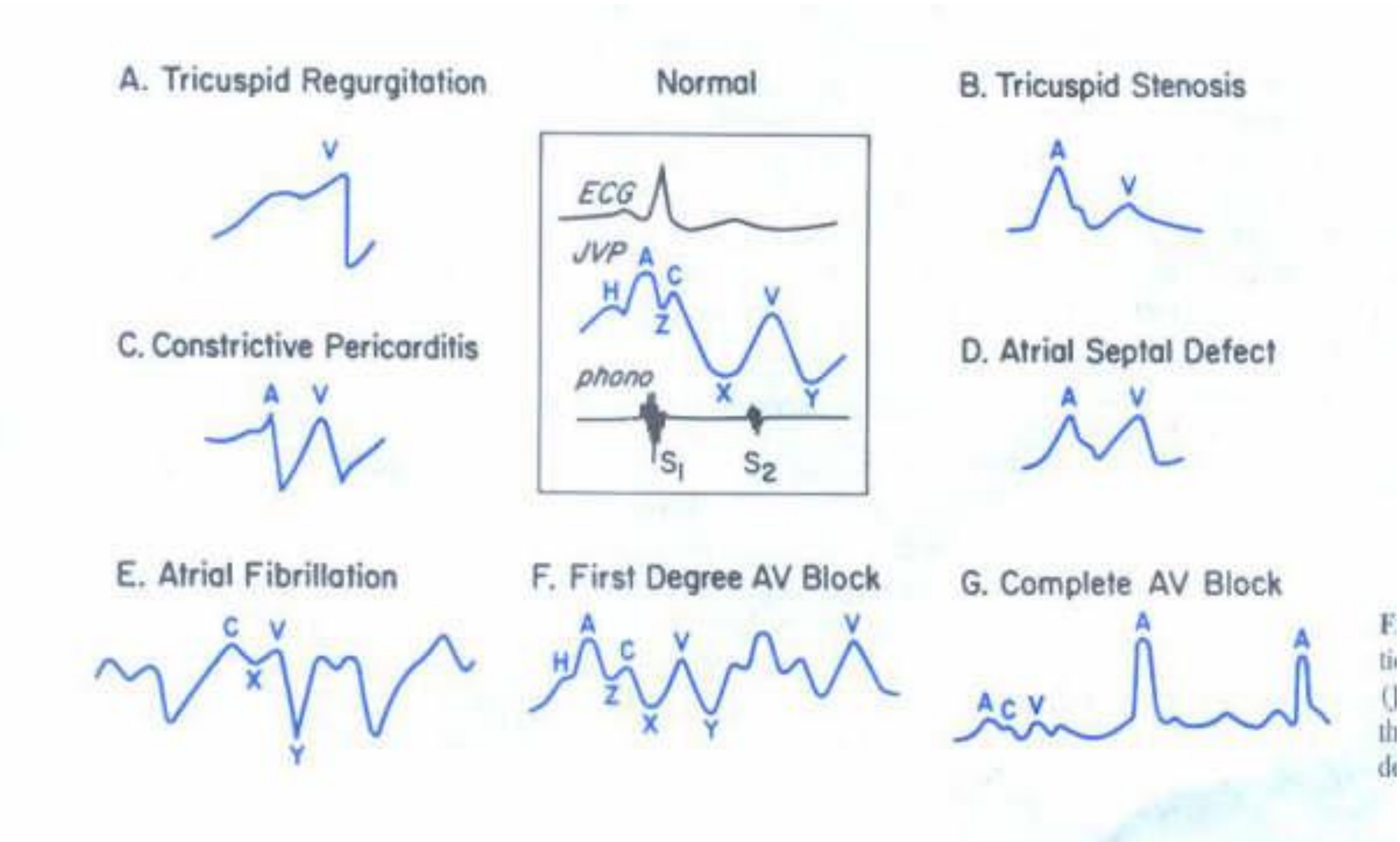
2. Cardiovascular:
   – Atrial or ventricular arrhythmia
   – Rupture of pulmonary arteries
   – Pulmonary infarct
   – Perforation of heart
   – Pulmonary embolism

   } **Rare**

Central venous pressure

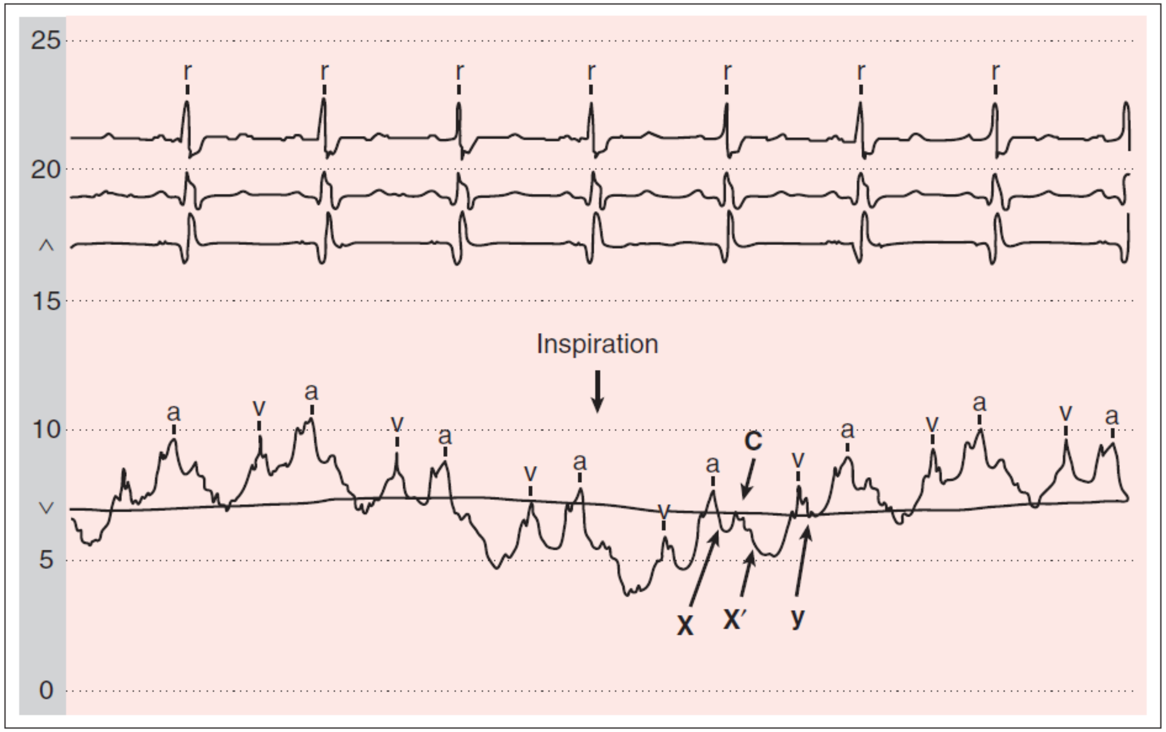


Abnormalities in RA Tracing



Inspiratory Effect on Pressure

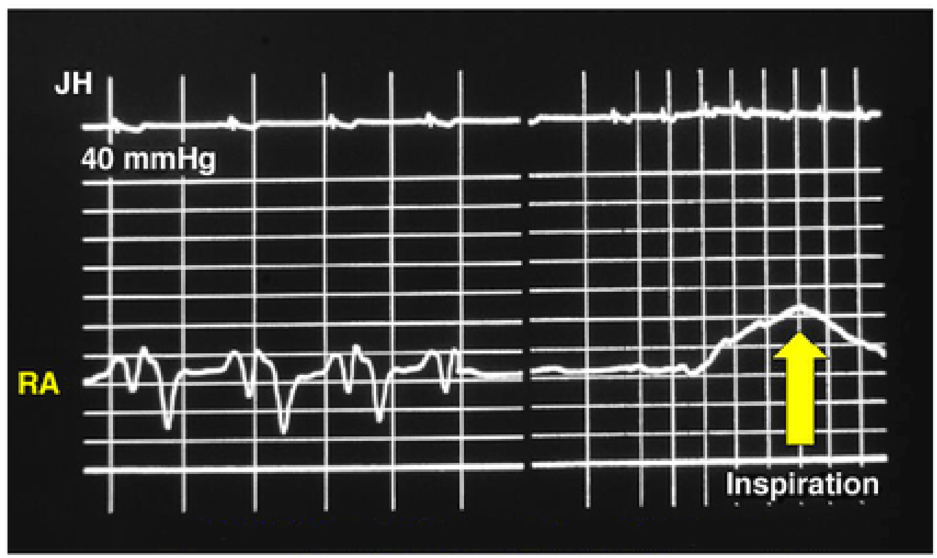
- Normal physiology
  - Inhalation: Intrathoracic pressure falls → RA pressure falls
  - Exhalation: Intrathoracic pressure increases → RA pressure increases



Braunwald's heart disease 9th edition

Abnormalities in RA Tracing

- Kussmaul's Sign
  - Inspiratory rise or lack of decline in RA pressure
  - Diagnostic for constrictive pericarditis or RV ischemia

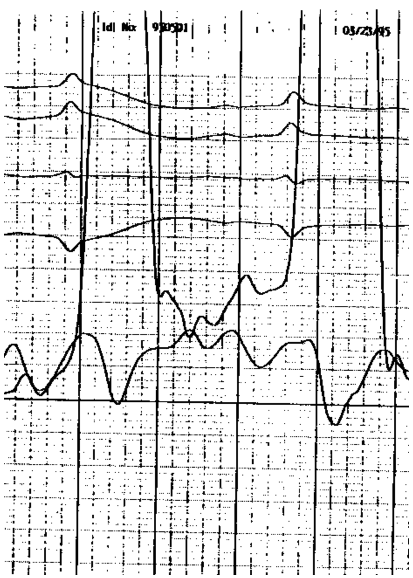


RA pressure elevated. M or W configuration
Kussmal's sign - inspiratory increase

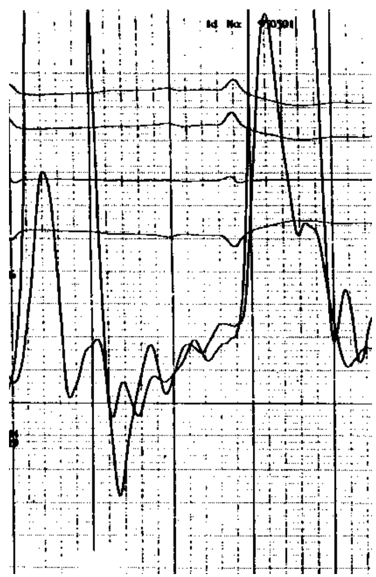
Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Abnormalities in RA Tracing

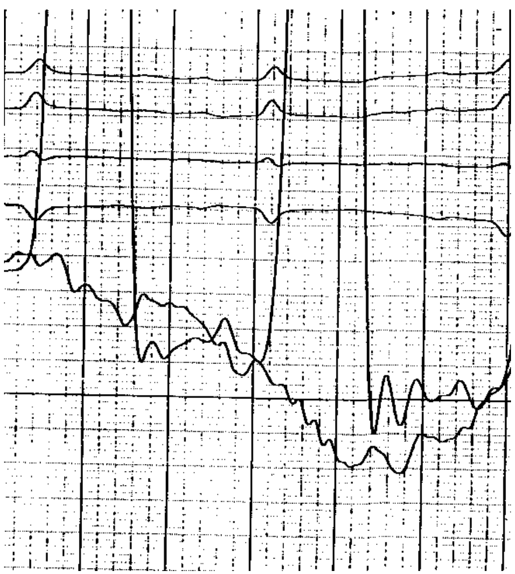
- Equalization of pressures
  - < 5 mm Hg difference between mean RA, RV diastolic, PA diastolic, PCWP, and pericardial pressures
  - Diagnostic for tamponade



RA and LV



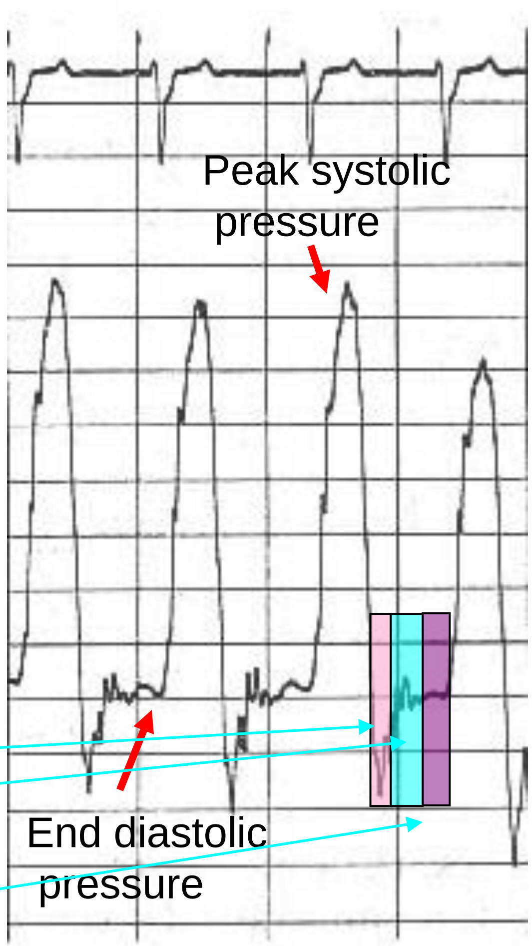
RV and LV



PCW and LV

Right ventricle pressure

- Systole
  - Isovolumetric contraction
    - From TV closure to PV opening
  - Ejection
    - From PV opening to PV closure
- Diastole
  - Isovolumetric relaxation
    - From PV closure to TV opening
  - Filling
    - From TV opening to TV closure
    - Early Rapid Phase
    - Slow Phase
    - Atrial Contraction ("a" wave")

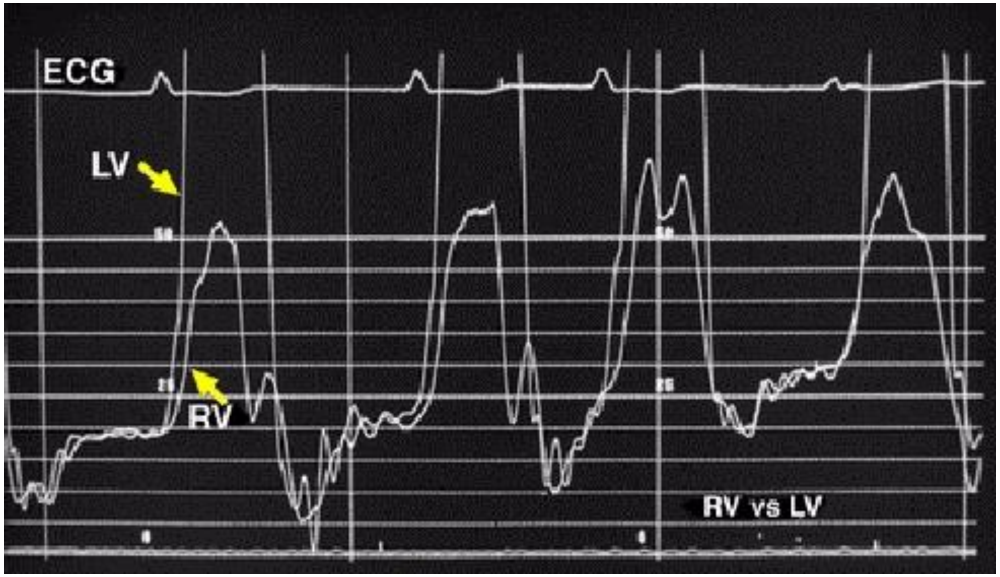


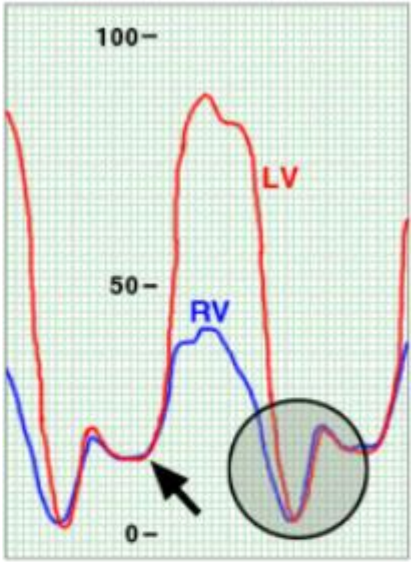
Abnormalities in RV Tracing

Dip and plateau in diastolic pressure wave

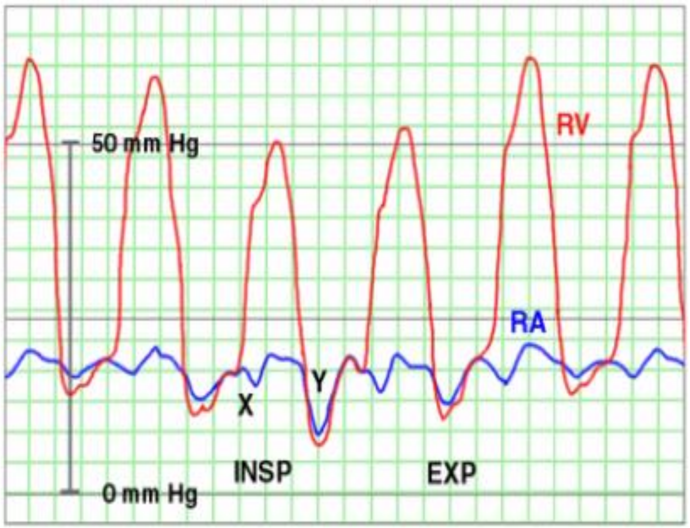
1. Constrictive pericarditis
2. Restrictive myopathies
3. Right ventricular ischemia
4. Acute dilation associated with
   a. Tricuspid regurgitation
   b. Mitral regurgitation

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

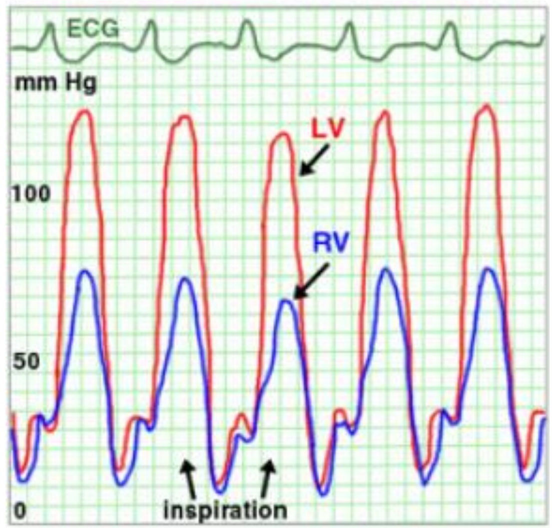




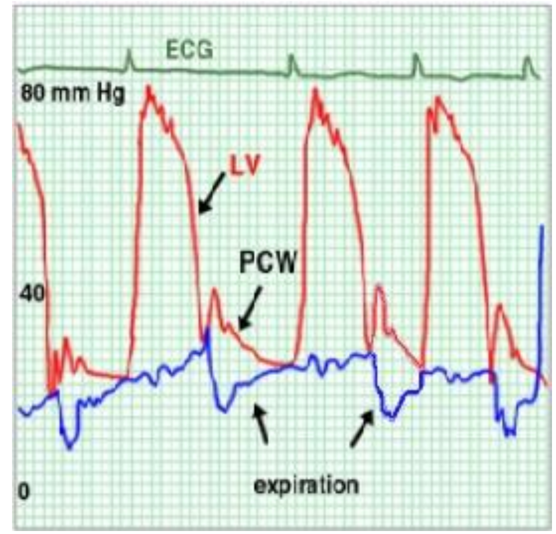
Restrictive Cardiomyopathy



- Prominent y descent
- Normal respiratory variation

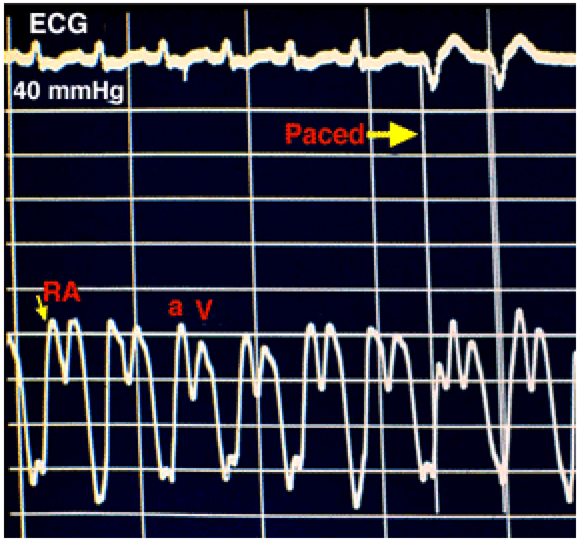


- Square root sign
- RVSP > 55 mm Hg
- RVEDP / RVSP < 1/3
- LVED-RVED > 5 mm Hg
- RV-LV interdependence absent

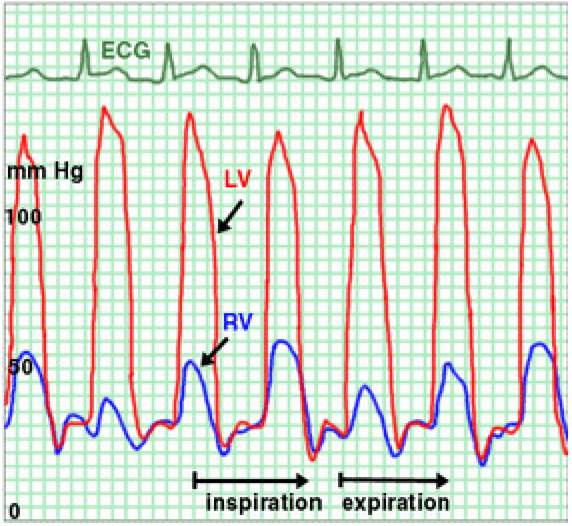


- Prominent y descent
- Lack of variation in early PCW-LV gradient

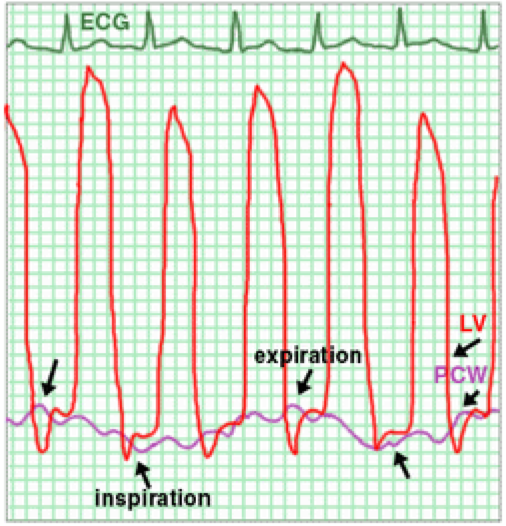
Constrictive Pericarditis



- Prominent x and y descents
- Equal a and v waves
- M wave morphology



- Square root sign
- RVSP < 55 mm Hg
- RVEDP / RVSP > 1/3
- LVED-RVED < 5 mm Hg
- RV-LV interdependence



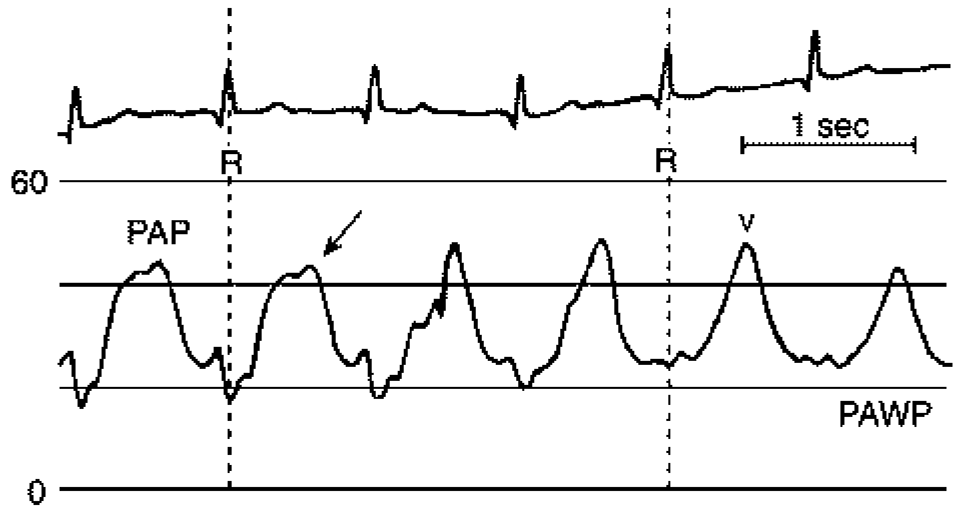
- Prominent y descent
- Variation in early PCW-LV gradient

Right Heart Catheterization
Right vs Left Ventricular Pressure

	Constrictive Pericarditis	Restrictive Cardiomyopathy
End diastolic pressure equalization (LVED-RVED)	≤ 5 mm Hg	> 5 mm Hg
Pulmonary artery pressure	< 55 mm Hg	> 55 mm Hg
RVEDP / RVSP	> 1/3	≤ 1/3
Dip-plateau morphology	LV rapid filling wave > 7 mm Hg	LV rapid filling wave ≤ 7 mm Hg
Kussmaul's sign	No respiratory variation in mean RAP	Normal respiratory variation in mean RAP

PA pressure

- Biphasic tracing
  - Systole
  - Diastole
- Pulmonary HTN
  - Mild: PAP > 20 mm Hg
  - Moderate: PAP > 35 mm Hg
  - Severe: PAP > 45 mm Hg



Diagnosis of PH/PAH

	2015 ESC guideline	2018 WSPH consensus
Mean PA pressure	≥ 25	> 20
Pulmonary artery wedge pressure	≦ 15	≦ 15
Pulmonary vascular resistance	≥ 3	≥ 3

1. However, the current consensus recommends to treat PAH patients who have mPAP ≥ 25mmHg according to the inclusion criteria of previous clinical trials.
2. There is no large-scale clinical trials to demonstrate treatment benefits in PAH patients who have mPAP between 20 and 25mmHg

Acute vasoreactivity test (1)

1. For idiopathic, hereditable or drug-induced PAH patients
2. Definition:
   1) Reduction of mPAP ⩾10 mmHg to reach an absolute value of mPAP ⩽40 mmHg
   2) Increased or unchanged cardiac output

European Heart Journal (2016) 37, 67–119

Acute vasoreactivity test (2)

Nitric oxide is recommended for performing vasoreactivity testing	I
Intravenous epoprostenol is recommended for performing vasoreactivity testing as an alternative	I
Adenosine should be considered for performing vasoreactivity testing as an alternative	IIa
Inhaled iloprost may be considered for performing vasoreactivity testing as an alternative	IIb

European Heart Journal (2016) 37, 67–119

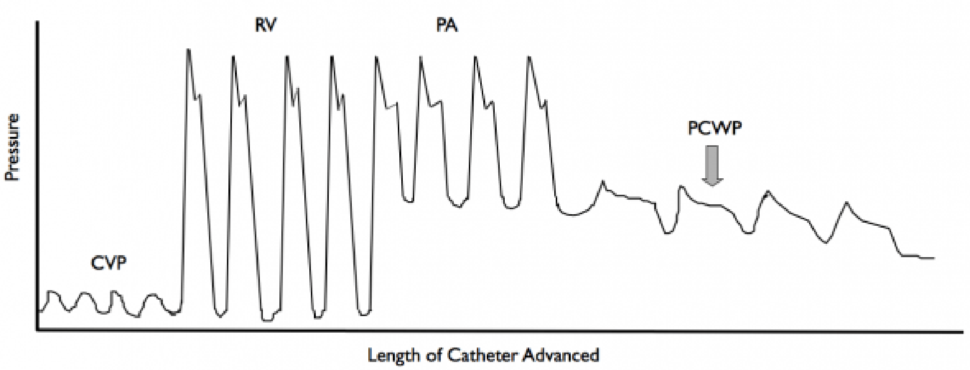
Acute vasoreactivity test (3)

Drug	Route	Half-life	Dosage range	Increments	Duration
Nitric Oxide	I.H.	15-30 s	10-20 p.p.m.	-	5 min
Epoprostenol	I.V.	3 min	2-12 ng/kg/min	2ng/kg/min	10 min
Adenosine	I.V.	5-10 s	50-350 mcg/kg/min	50mcg/kg/min	2 min

 European Heart Journal (2009) 30, 2493–2537

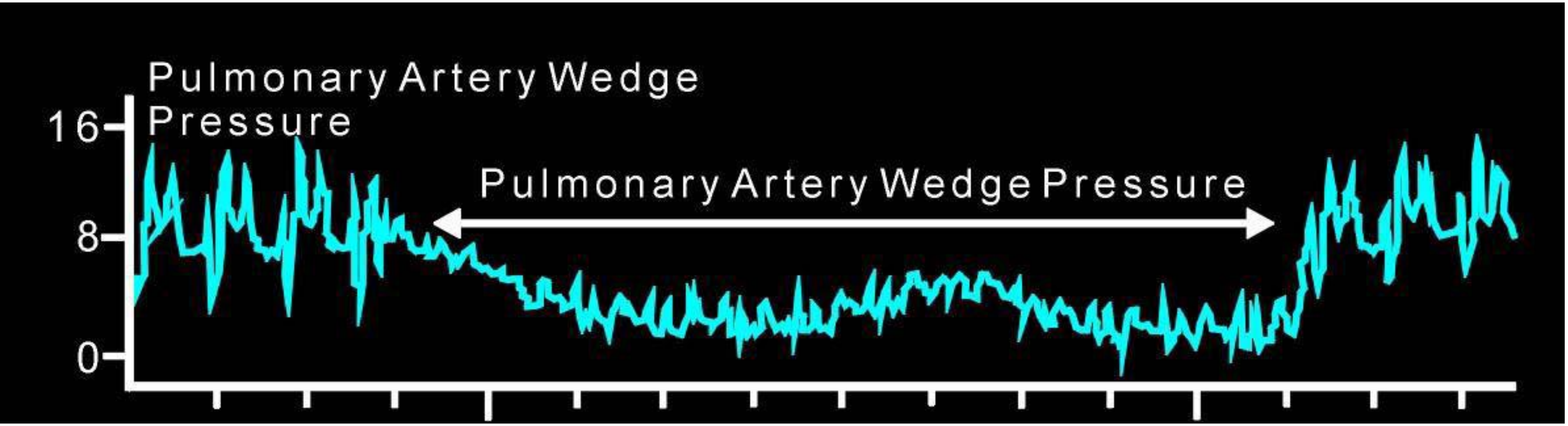
Abnormal PA pressure

- Reduced pulse pressure
  - Right heart ischemia
  - RV infarction
  - Pulmonary embolism
  - Tamponade
- PA diastolic pressure > PCW pressure
  - Pulmonary disease
  - Pulmonary embolus
  - Tachycardia



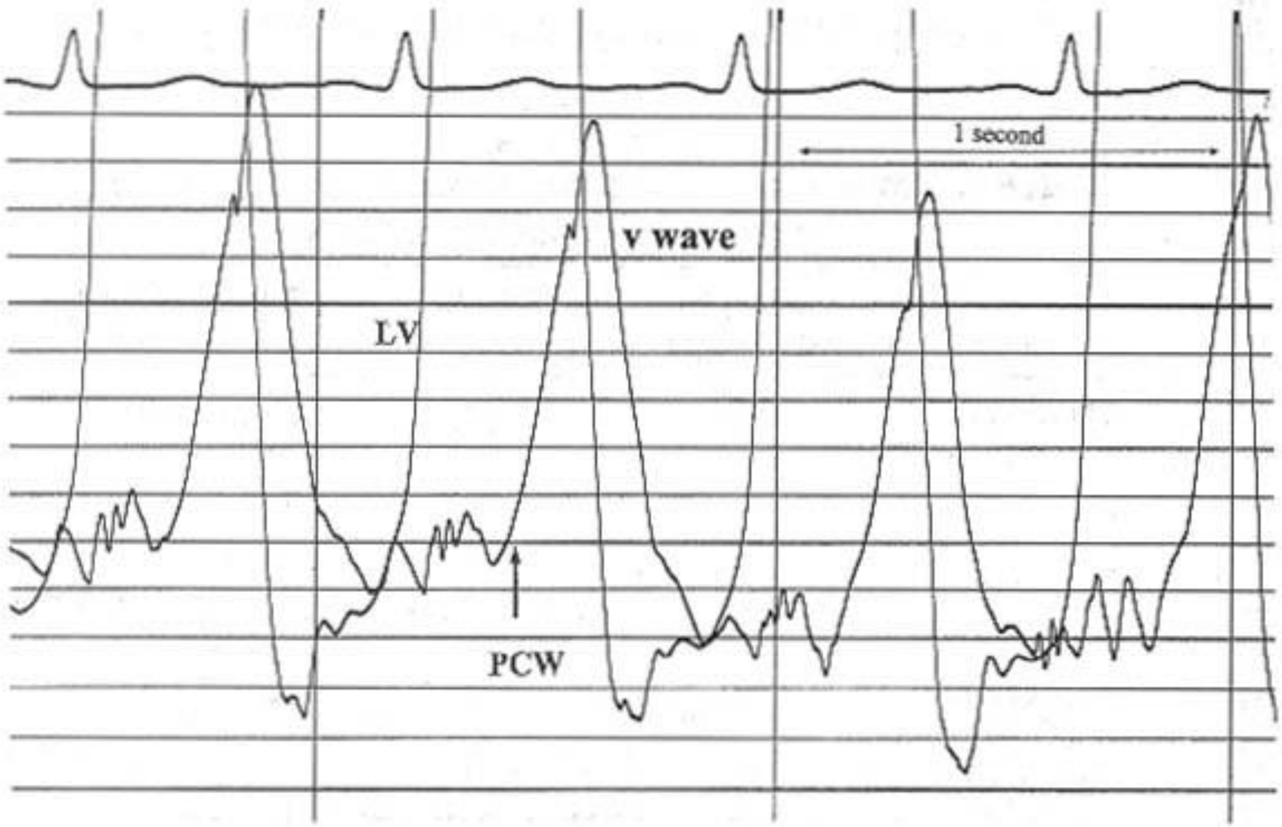
Wedge Pressure

- a wedge pressure is obtained when an end-hole catheter is positioned in a designated blood vessel with its open end-hole facing a capillary bed
- A true wedge pressure can be measured only in the absence of flow



Abnormalities in PCWP Tracing

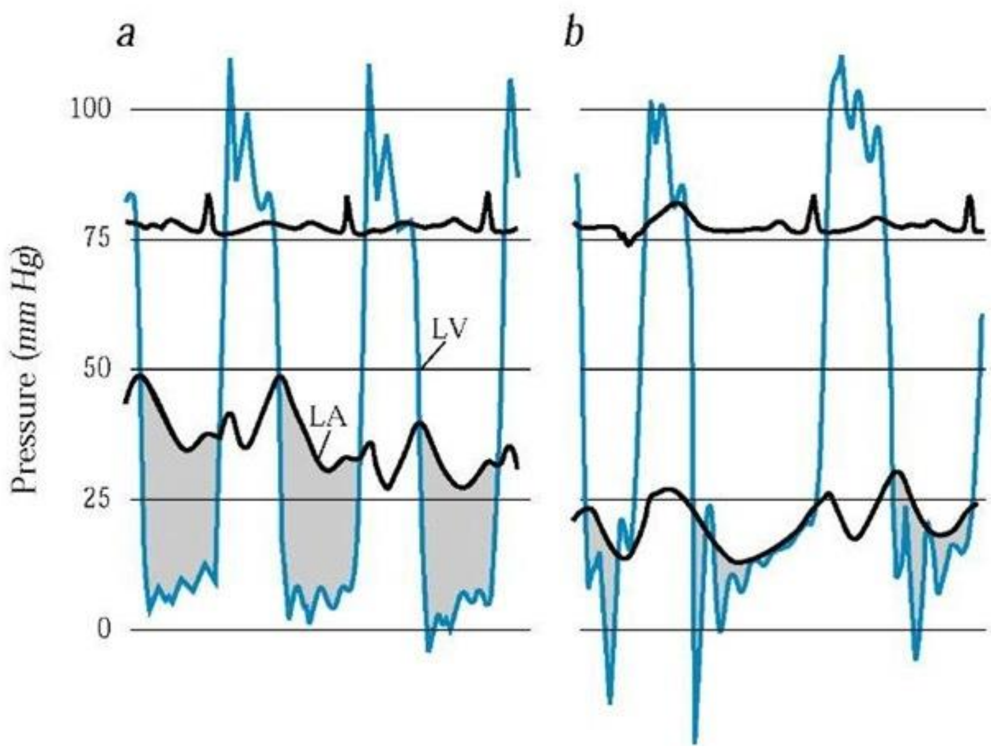
- Severe Mitral Regurgitation



Davidson CJ, et al. Cardiac Catheterization.
In: Heart Disease: A Textbook of Cardiovascular Medicine,
Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Abnormalities in PCWP Tracing

- PCWP not equal to LV end diastolic pressure
  - Mitral stenosis
  - Atrial myxoma
  - Cor triatriatum
  - Pulmonary venous obstruction
  - Decreased ventricular compliance
  - Increased pleural pressure

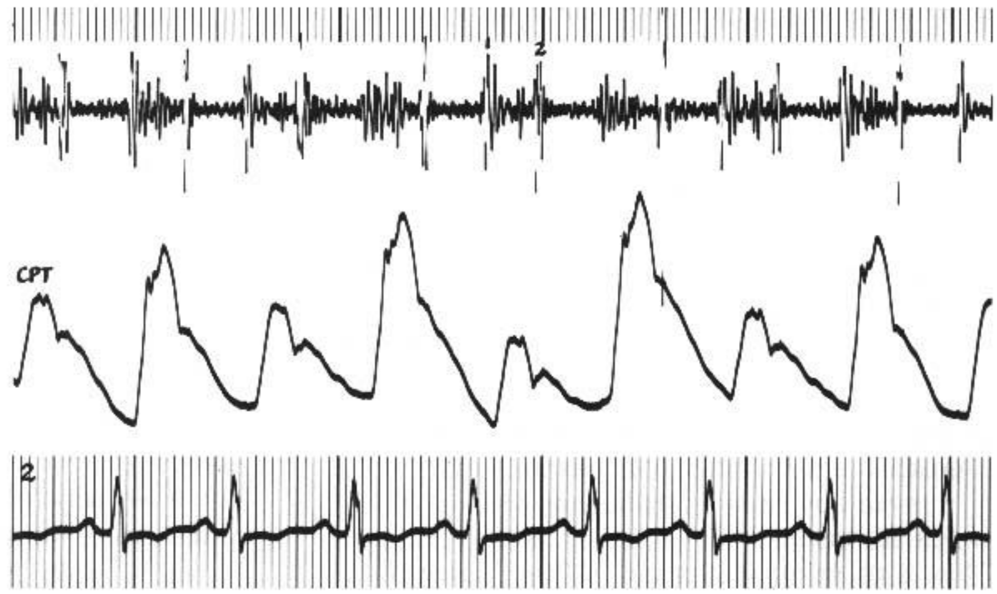


Incorrect measurement PAWP

1. PAWP
   - Measurement at end-expiratory period
   - PCWP is unexpected high
     - PCWP is usually lesser than PA diastolic pressure (PADP)
     - If PCWP is greater than PADP, may indicate damping or incorrect position of the tip of PCWP
2. Unable to measure PCWP
   - Measure LV end-diastolic pressure

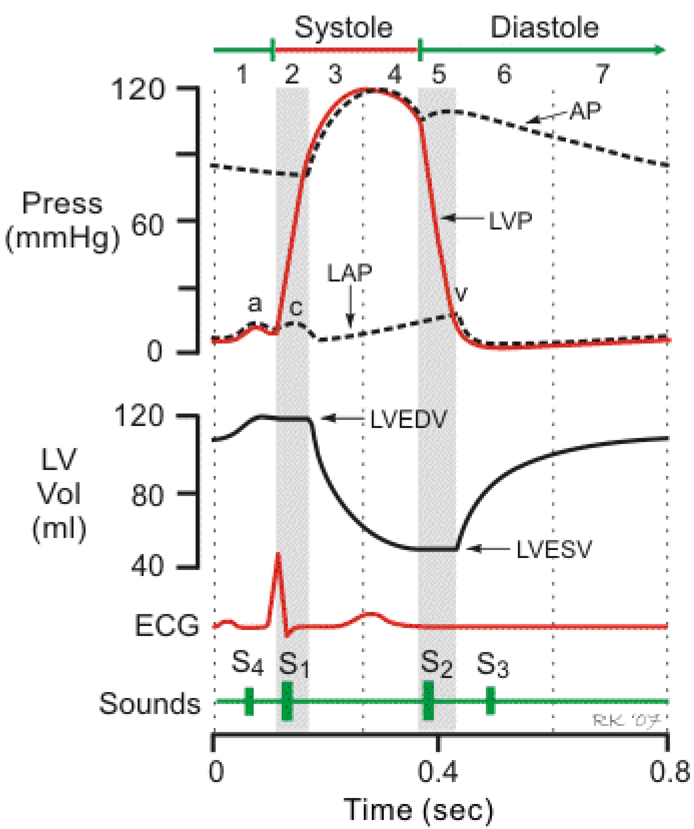
Arterial Pressure Monitoring
Abnormalities in Central Aortic Tracing

- Pulsus alternans
  - Pericardial effusion
  - Cardiomyopathy
  - CHF

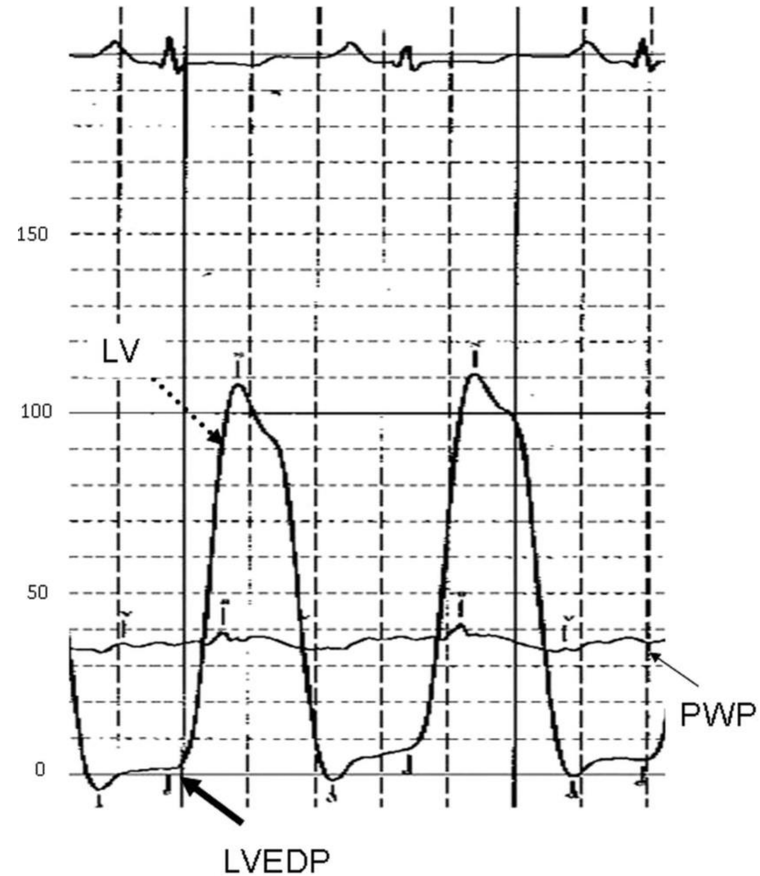


Marriott HJL. Bedside Cardiac Diagnosis. Philadelphia: JB Lippincott Company, 1993.

LVEDEP

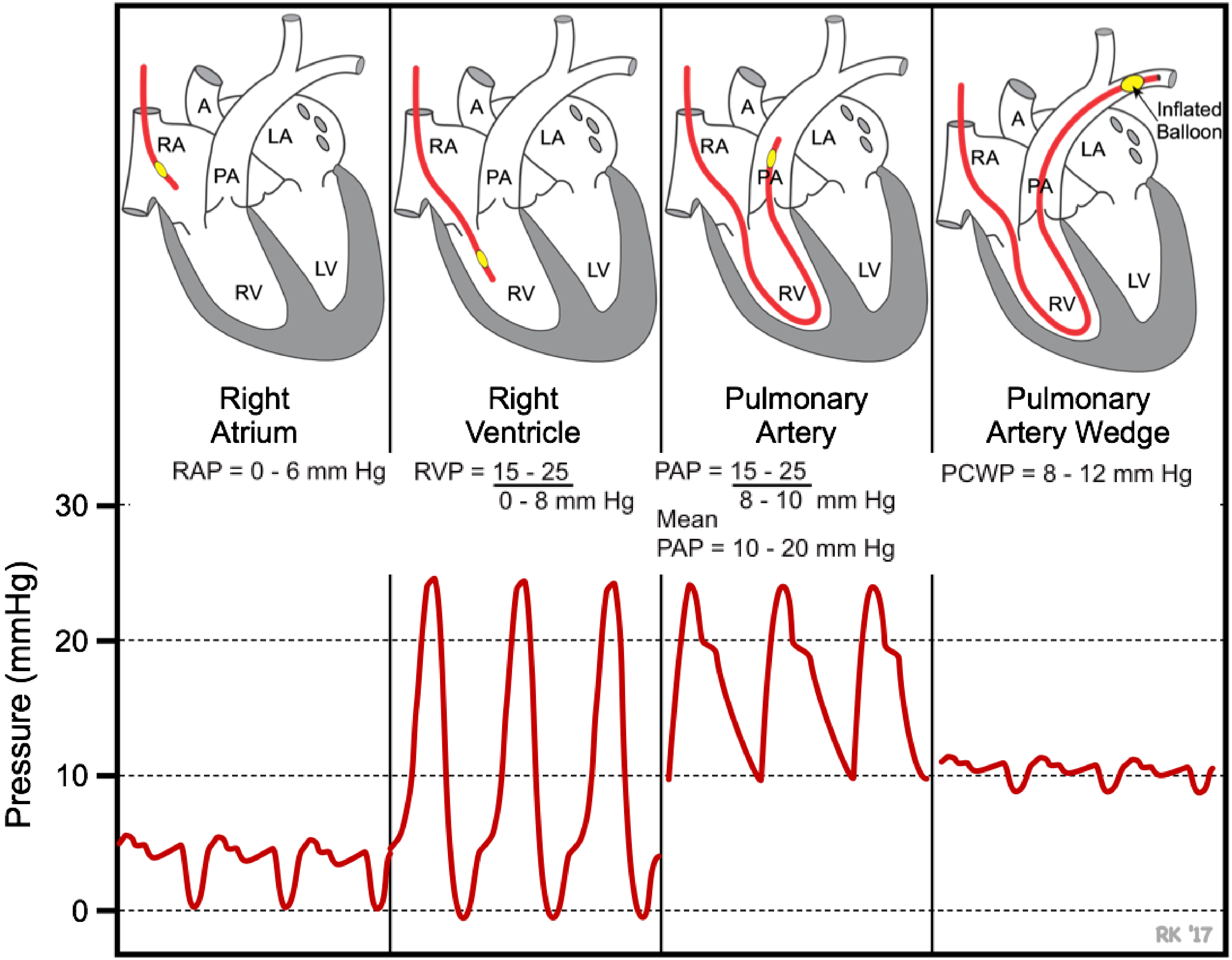


Systole
Diastole
1 2 3 4 5 6 7
120
Press (mmHg)
60
0
AP
LVP
LAP
a
c
v
120
LV Vol (ml)
80
40
LVEDV
LVESV
ECG
S4 S1 S2 S3
Sounds
0
0.4
0.8
Time (sec)



150
100
50
0
LV
PWP
LVEDP

How to measure LVEDP


A
RA
LA
PA
RV
LV
Inflated Balloon
Right Atrium
Right Ventricle
Pulmonary Artery
Pulmonary Artery Wedge
RAP = 0 - 6 mm Hg
RVP = 15 - 25 / 0 - 8 mm Hg
PAP = 15 - 25 / 8 - 10 mm Hg
Mean PAP = 10 - 20 mm Hg
PCWP = 8 - 12 mm Hg
Pressure (mmHg)
30
20
10
0
RK '17

Hemodynamic Parameters Reference Values

	Average	Range
Right atrium		
a wave	6	2 - 7
v wave	5	2 - 7
mean	3	1 - 5
Right ventricle		
peak systolic	25	15 - 30
end diastolic	4	1 - 7
Pulmonary artery		
peak systolic	25	15-30
end diastolic	9	4-12
mean	15	9-19

	Average	Range
PCWP		
mean	9	4 - 12
Left atrium		
a wave	10	4 - 16
v wave	12	6 - 21
mean	8	2 - 12
Left ventricle		
peak systolic	130	90 - 140
end diastolic	8	5 - 12
Central aorta		
peak systolic	130	90 - 140
end diastolic	70	60 - 90
mean	85	70 -105

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Cardiac Output Measurements

- There is no completely accurate method of measuring cardiac output
- C.O can be estimated on the basis of various assumptions
- C.O. measurement
  ① **Thermodilution method**
  ② **Fick method**
  ③ **Angiographic Cardiac Output**

Cardiac Output Measurement
Thermodilution Method

$$CO = \frac{V_I\,(T_B - T_I)\,(S_I \times C_I \,/\, S_B \times C_B)\times 60}{\int_0^{\infty} \Delta T_B \, dt}$$

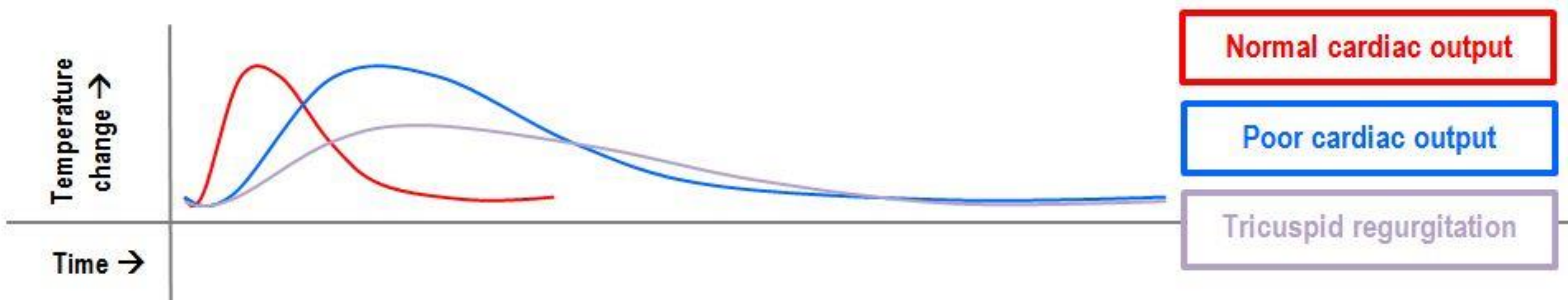
V_I = volume of injectate

S_I, S_B = specific gravity of injectate and blood

C_I, C_B = specific heat of injectate and blood

T_I = temperature of injectate

ΔT_B = change in temperature measured downstream



Cardiac Output Measurement Thermodilution Method

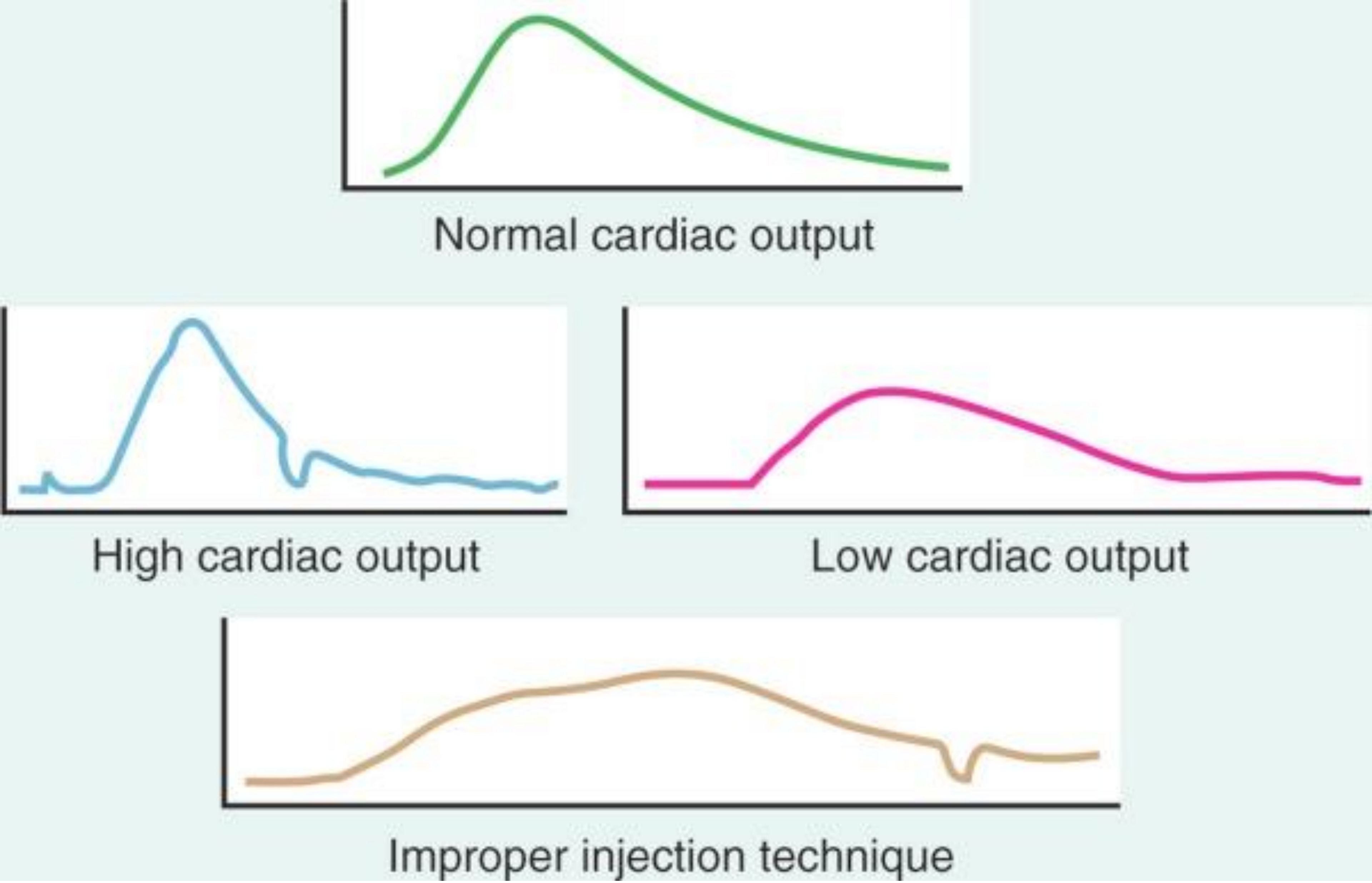
- Advantages
  - Withdrawal of blood not necessary
  - Arterial puncture not required
  - Indicator (saline or D5W)
  - Virtually no recirculation, simplifying computer analysis of primary curve sample
  - rapid display of results with computerized methods

Cardiac Output Measurement Thermodilution Method

- Sources of Error (± 15%)
  - Unreliable in tricuspid regurgitation
  - Baseline temperature of blood in pulmonary artery may fluctuate with respiratory and cardiac cycles
  - Loss of injectate with low cardiac output states (CO < 3.5 L/min) due to warming of blood by walls of cardiac chambers and surrounding tissues. The reduction in ΔT_B at pulmonary arterial sampling site will result in overestimation of cardiac output
  - Empirical correction factor (0.825) corrects for catheter warming but will not account for warming of injectate in syringe by the hand

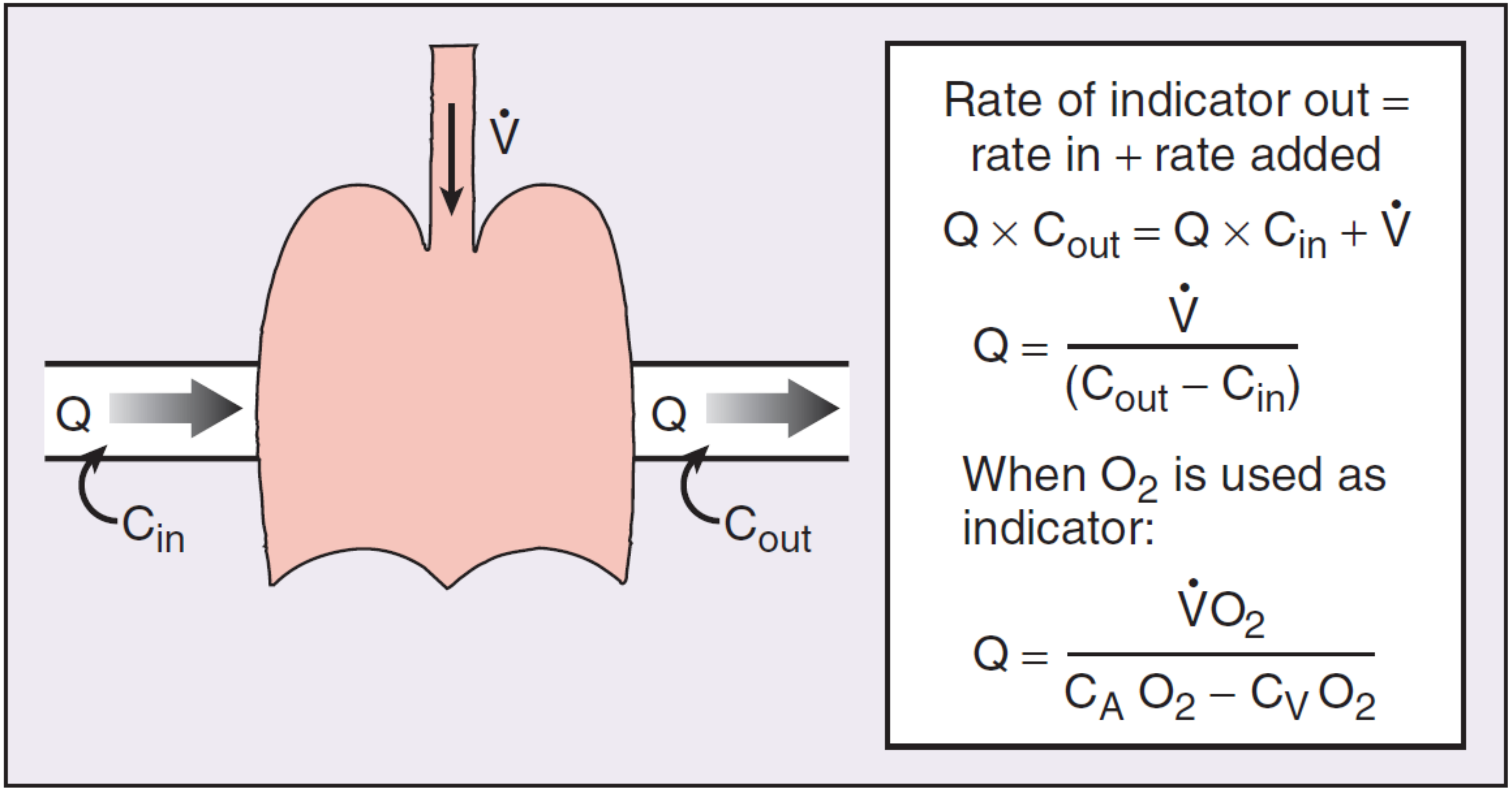
Thermodilution method

1. Caveats:
   1) Overestimate CO in low CO status
   2) Underestimate CO in severe TR
2. Fluid injections:
   1) The amount of injections depends on the setting on the machine
   2) The temperature of 0.9% saline:
      - At least 10℃ less than body temperature
      - Icy water is preferred



The Cardiac output is inversely related to the area under a thermodiluation

Cardiac Output Measurement
FICK METHOD



假設: O2 consumption is a function of the rate of blood flow times the rate of oxygen pick-up by the red blood cells

Fick method

$$CO = \frac{O_2\ consumption}{1.36 * 10 * Hb * (SaO2 - SvO2)}$$

- SaO_2: saturation of artery
- SvO_2: saturation of pulmonary artery
- Hgb: hemoglobin concentration (mg/dL)
- oxygen-carrying capacity of hemoglobin: 1.36 mL O2/g Hgb

Fick method

假定O2 consumption、Hb及SaO2不變，

1. SvO2越低，分母越大，所以CO越低
2. SvO2越高，分母越大，所以CO越高

使用注意事項：

1. 不可有嚴重的arterial-venous shunt，如先天性心臟病或是嚴重敗血症
2. SvO2 可以用ScvO2代替 (ScvO2 obtained at SVC)

Mixed venous O2

- Flamm formula

$$MVO_2 = \frac{3(\text{SVC } O_2 \text{ content}) + 1(\text{IVC } O_2 \text{ content})}{4}$$

Cardiac Output Measurement FICK METHOD

- Advantage
  - the most accurate method in patients with low cardiac output
  - Independent of the factors that affect curve shape and cause errors in thermodilution cardiac output
- Disadvantage
  - Accurate oxygen consumption measurements
  - Not for patients with significant MR, AR
  - Not suitable during rapid changes in flow
  - Patient cannot be receiving supplemental oxygen

“assumed” Fick method,

- oxygen consumption index is assumed on the basis of the patient’s age, gender, and body surface area or an estimate is made (125 mL/m2) on the basis of body surface area
- large errors can occur…..

Cardiac Output Measurement
Stroke Volume

- Stroke Volume
  - Volume of blood ejected in a single contraction
  - Volumetric analysis requires 3-dimensional analysis to calculate end-diastolic and end-systolic volume

Stroke volume = End-diastolic volume – End-systolic volume

  - Estimation based on cardiac output

$$\text{Stroke volume} = \frac{\text{Cardiac output}}{\text{Heart rate}}$$

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Vascular Resistance
Definitions

Systemic vascular resistance

$$SVR = \frac{\overline{Ao} - \overline{RA}}{Q_s}$$

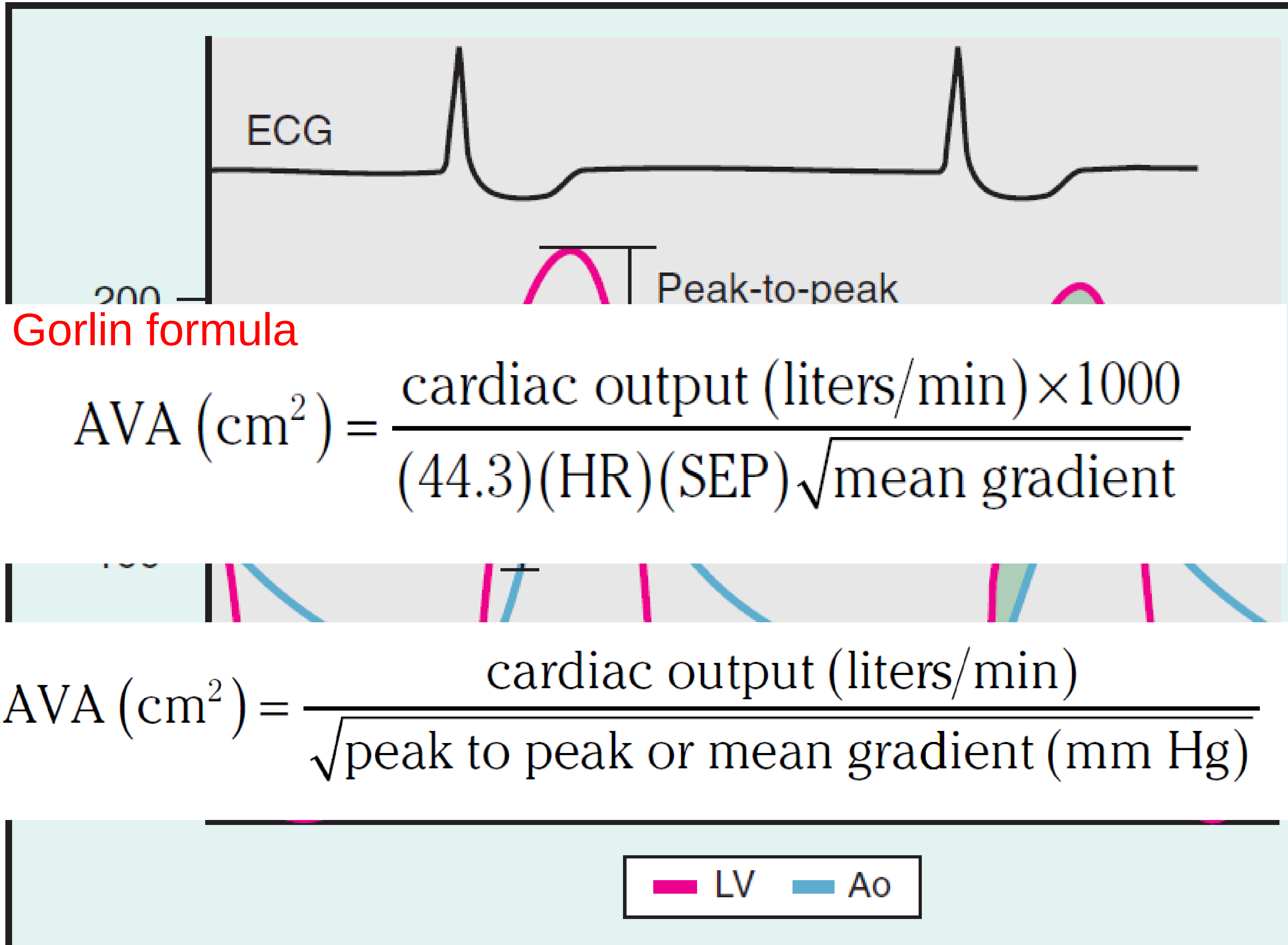
Pulmonary vascular resistance

$$PVR = \frac{\overline{PA} - \overline{LA}}{Q_p}$$

Normal reference values

	Woods Units	x 80 =	Metric Units
SVR	10 – 20		770 – 1500
PVR	0.25 – 1.5		20 – 120

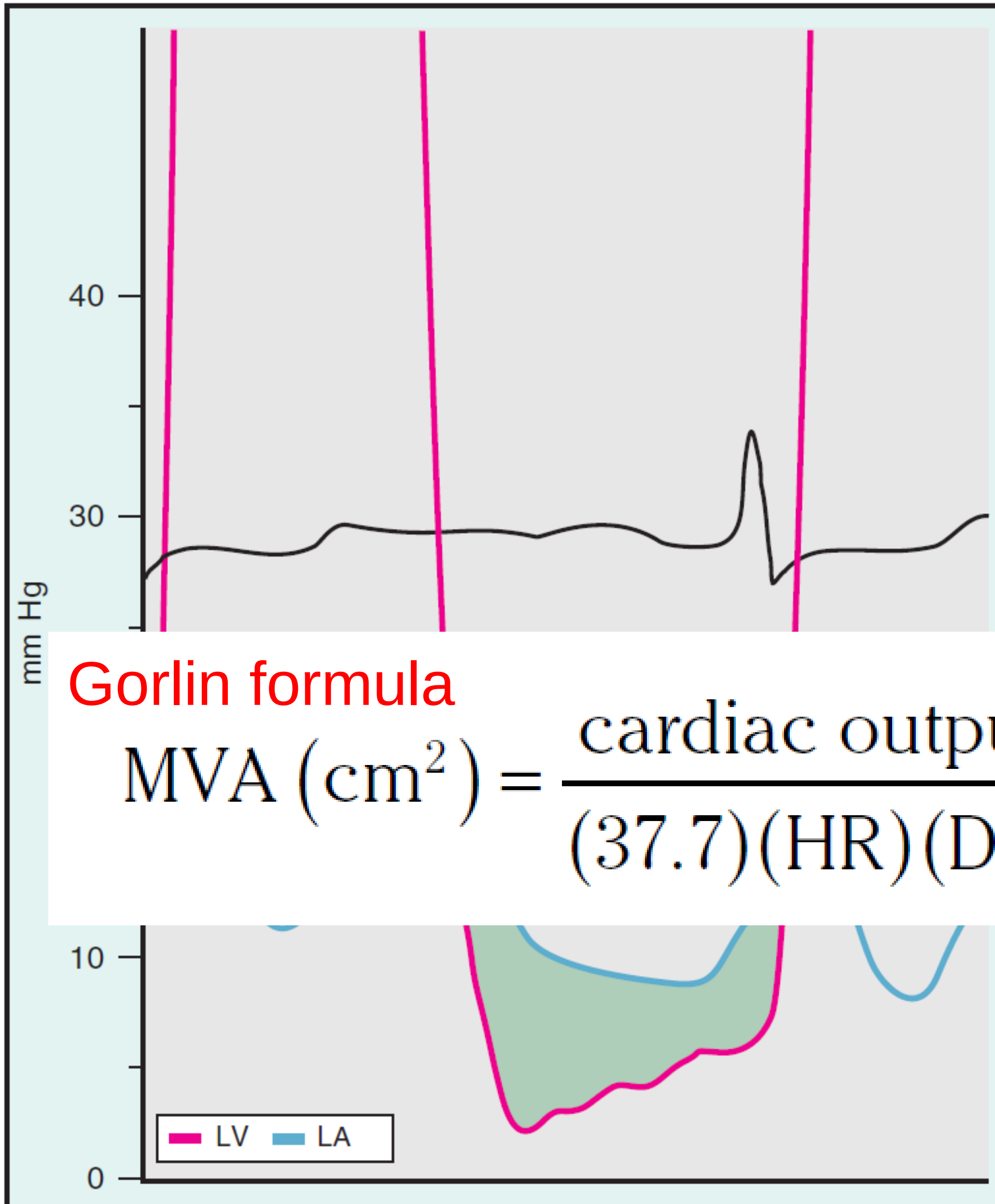
Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.



Gorlin formula

$$\text{AVA}\,(\text{cm}^2) = \frac{\text{cardiac output (liters/min)} \times 1000}{(44.3)(\text{HR})(\text{SEP})\sqrt{\text{mean gradient}}}$$

$$\text{AVA}\,(\text{cm}^2) = \frac{\text{cardiac output (liters/min)}}{\sqrt{\text{peak to peak or mean gradient (mm Hg)}}}$$

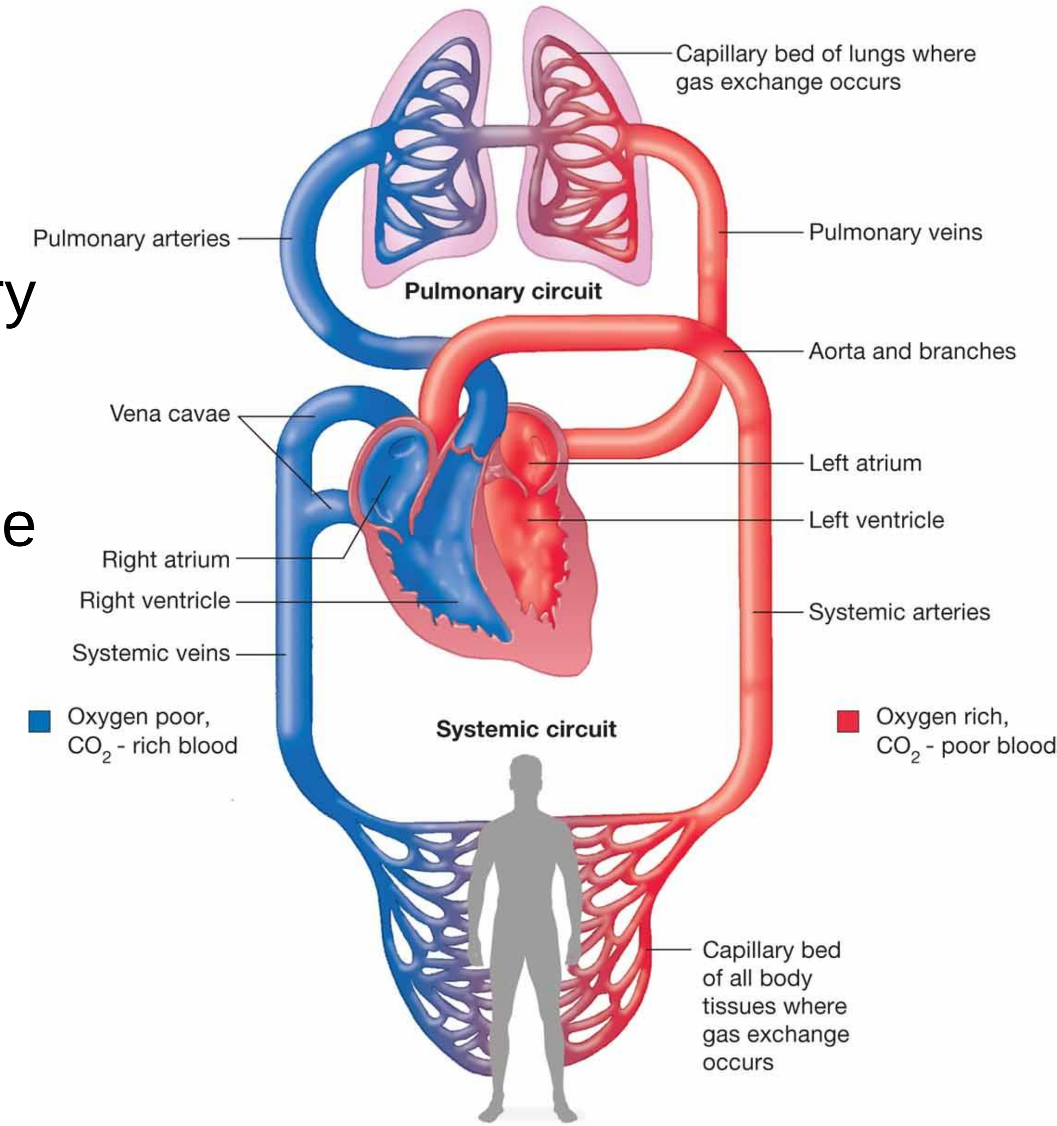


Gorlin formula

$$MVA\ (cm^2) = \frac{\text{cardiac output (liters/min)} \times 1000}{(37.7)(HR)(DFP)\sqrt{\text{mean gradient}}}$$

Curculation Shunt

- shunted from the systemic circulation to the pulmonary circulation (left-to-right shunt)
- pulmonary circulation to the systemic circulation (right-to-left shunt)
- in both directions

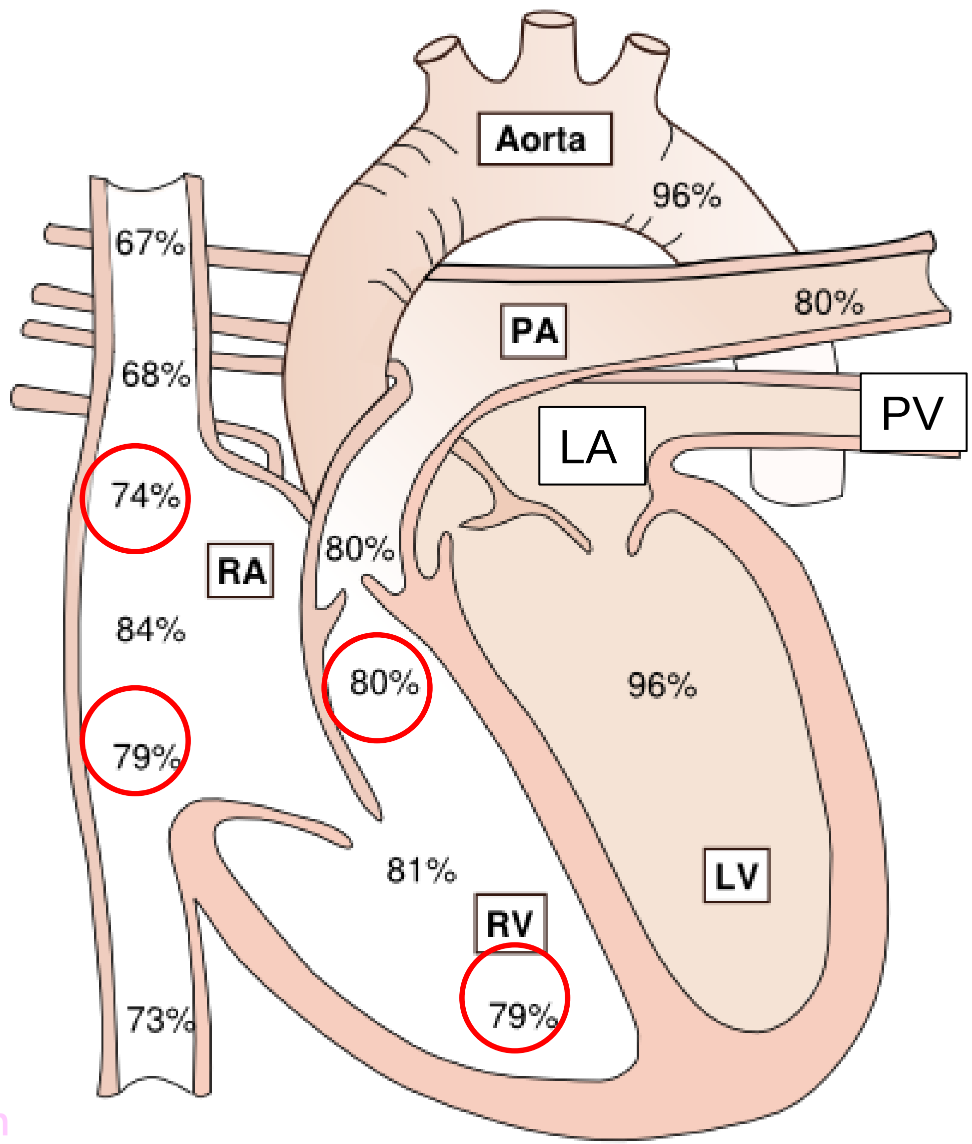


Shunt quantitation

- **Oximetric Method**
- **Indicator-Dilution Method**

Oximetric method

- most commonly used method
- Vigilant for unexpected findings
- PA-SVC difference >8%
- RA 3 sites
- RV 3 sites



Shunt Quantification

Base on FICK METHOD

Pulmonary blood flow

$$PBF = \frac{O_2 \text{ consumption}(mL/min)}{(PVO_2 - PAO_2)}$$

Systemic blood flow

$$SBF = \frac{O_2 \text{ consumption}(mL/min)}{(SAO_2 - MVO_2)}$$

Effective blood flow

$$EBF = \frac{O_2 \text{ consumption}(mL/min)}{(PVO_2 - MVO_2)}$$

pulmonic-to-systemic blood flow ratio

- The flow ratio PBF/SBF (or Qp/Qs)

$$Q_p/Q_s = PBF/SBF = \frac{(SAO_2 - MVO_2)}{(PVO_2 - PAO_2)}$$

- Qp/Qs <1.5 : small
- Qp/Qs 1.5-2: moderate
- Qp/Qs>2: large

Saturation Run

- Obtain Samples from…
  - IVC: High and Low
  - SVC: High and Low
  - Right Atrium: High, Middle and Low
  - Right Ventricle: Inflow and Outflow tracts, mid-cavity
  - Pulmonary Artery: Main, Left or Right
- Localizing Right to Left Shunts one should also obtain….
  - Pulmonary Vein
  - Left Atrium
  - Left Ventricle
  - Distal Aorta
- Slow….

Summary

- Hemodynamics measurement is a roadmap to correct clinical judgment
- Correct information is important
- Evaluation of hemodynamics include “value”, “waveforms”, “oxygenation”, “ cardiac output” and “global data review”.