Applied Physiology and Hemodynamics

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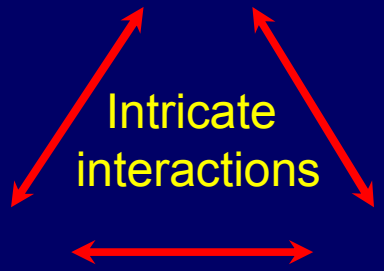
Cardiovascular System

Structure and Function
(構造及功能)

Mechanical
(機械)



Electrical
(電氣)

Perfusion
(灌流)

Neuro-humoral regulations
Autonomic nervous system
Endocrine-humoral – catecholamines, RAS, natriuretic peptides, endothelin etc.

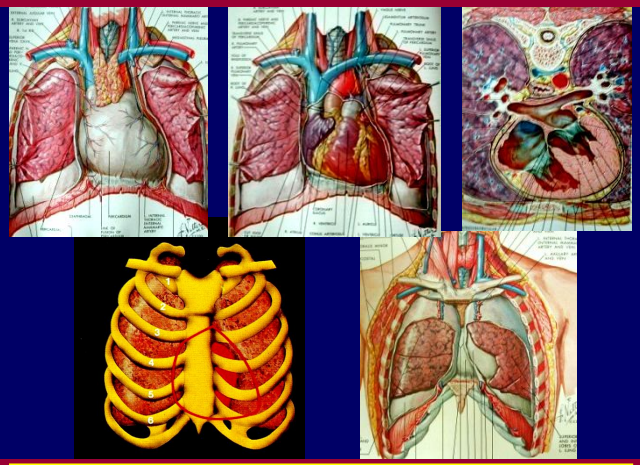
*緊密的互動

問題之剖析、診斷
方法 (Means)

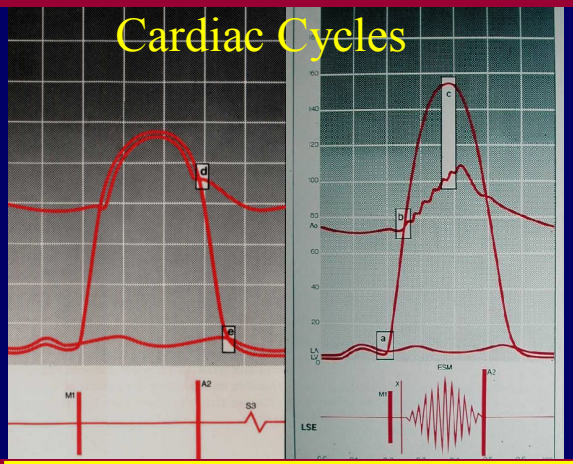
1. 病史 (history)
2. 身體診查
   (physical Exam)
3. 實驗室檢查
   (laboratory tests)
   Proper (適當性)
   Timely (適時性)

實驗室檢查 (Imagings)*

Physical Exam in CV System



Applied Anatomy



1. Hemodynamic Pressure
2. Volumetric flow
3. Hemodynamic resistance
4. Compliance
5. LaPlace law
6. Poiseuille's Law

Applied Physiology and Hemodynamics

Fundamentals in Clinical Cardiology

*ECG, radiographs, echo, CT, MRI etc.

Applied Physiology and Hemodynamics

1. Hemodynamic Pressure
2. Volumetric flow
3. Hemodynamic resistance
4. Compliance
5. Laplace law
6. Poiseuille's Law

壓力(Pressure)

Applied Olm's Law (pressure/flow/resistance, triangle relationships)

$P_1 = F \times R + P_2$

[P: 壓力; F: 流量; R: 阻抗]

Systemic circulation

BP = CO x SVR + RA

BP* ~ CO x SVR (BP >> RA, 因此 RA 省略)

Pulmonary circulation

PAP = CO x PAR + PVP (PAWP)

PVP (PAWP) = LVDP + Ro (≥ 0)

Systemic venous system

VP** = F x R [*RA + Ro (≥ 0)]

PAP = pulmonary arterial pressure
PAR = pulmonary arteriolar resistance
PVP = pulmonary venous pressure
VP = venous pressure

Vascular Reisisance (R)

R_f = Functional (機能性)

Ro = Organic (器質性)

intramural, mural, extramural

Blood Pressure (血壓)

Non-invasive, indirect assessment of aortic pressure

Assumptions:

1) Reliable cuff sphygmomanometer
2) Correct measurement technique
3) No obstruction between aorta and arm
4) Adequate minimal blood flow – no extreme arterial vasoconstriction

Parameters, derived from BP measurements:

Direct: 1) Systolic pressure; 2) Diastolic pressure

Indirect: 3) Pulse pressure (PP) (systolic – diastolic pressure)

Assumptions: 動脈如果無阻塞或無嚴重收縮 – 脈壓反映脈搏大小

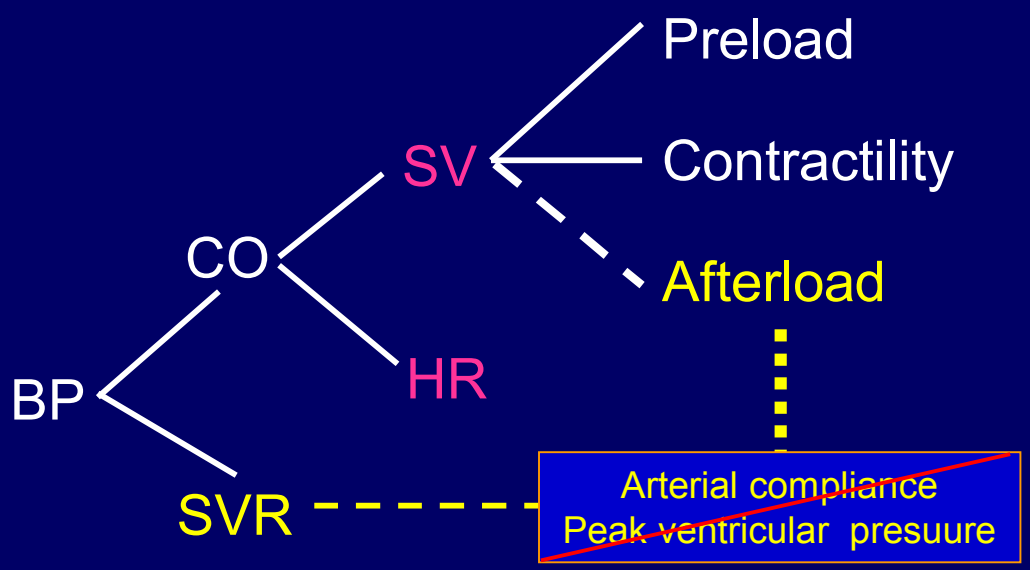
Potential pitfalls, if the above assumptions are not met

To avoid pitfalls:

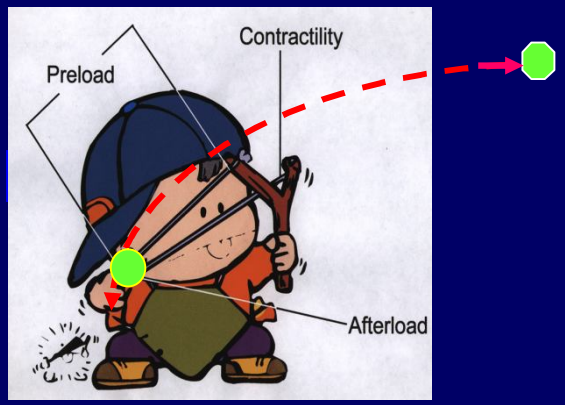
1) Establish a habit of palpating 6-site pulses:
   a) right and left carotid, individually;
   b) right radial/femoral, simultaneously
   c) left radial/femoral, simultaneously

2) Be certain, BP and pulse amplitudes are correlated

BP = f (SVR, HR, preload, afterload, contractility)



Hung's
"Slingshot Cardiac Physiology"



Afterload, mainly determined by SVR

Thus, In practicality,

BP = f (SVR, HR, preload, ~~afterload~~, contractility)

unless presence of significant LV outflow resistance

Primary Mechanism of Hypotension in Shock

	HR[c]	Preload	Contractility	PVR
1) Hypovolemic		↓		
2) Obstructive[a]		↓		
3) Cardiogenic[b]			↓	
4) Distributive				
a) Septic[b]		↓	N → ↓	↓ → ↑
b) Neurogenic	↓	↓		↓
c) Anaphylactic		↓		↓

a - among 2), most easily and effectively treatable:
b - toughest to treat
c - most easily assessed, including arrhythmia

tension pneumothorox
tamponade – be alert!

Pulmonary Artery Hypertension (PAH)

Increased mean pulmonary arterial pressure

mPAP > 25 mm Hg

PCWP <15 mm Hg, and

Pulmonary arteriolar resistance (PA_oR)

$\geq$ 240 dynes/s/cm^2

or, 3 Wood units (mmHg/L)

PAP = CO x PAR + PVP (PAWP)

Pulmonary Venous Congestion - Left Heart Failure

Pathophysiology – Cardiogenic pulmonary edema
Increased pulmonary capillary & venous pressure (PVP)
PVP (PAWP) = F x *R (downstream resistance)

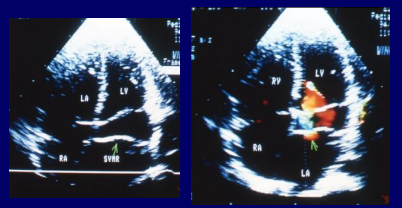
*Resistance

2-channel recording

Organic（器質性）: PAWP > LVDP

Pulmonary venous system (veins and venules) obstruction
Pulmonary veno-occlusive disease
Mediastinal fibrosis thrombophlebitis Post-RFCA
Cor triatriatum Supravalvular (mitral) ring
MV obstruction – valvular stenosis, thrombus, myxoma

Organic resistance
1) intraluminal
2) mural
3) extramural



Functional（機能性）: PAWP = LVDP

LV failure – systolic and/or diastolic dysfunction
Pericardial compressive syndrome
Cardiac tamponade
Chronic constrictive pericardiitis

Heart failure
= LV failure ?

Examination of Jugular Veins

Internal jugular vein - direct drainage to RA
External jugular vein –
1) indirect drainage to RA (detour 迂迴)
2) Presence of valves

CVP line
mother nature

*Jugular Venous Pressure

Arterial pressure
Intravascular volume
Venous capacitance
Right heart
hemodynamics
TV staus
RV
Pleural/pericardial
pressure

Internal jugular vein

To Assess:

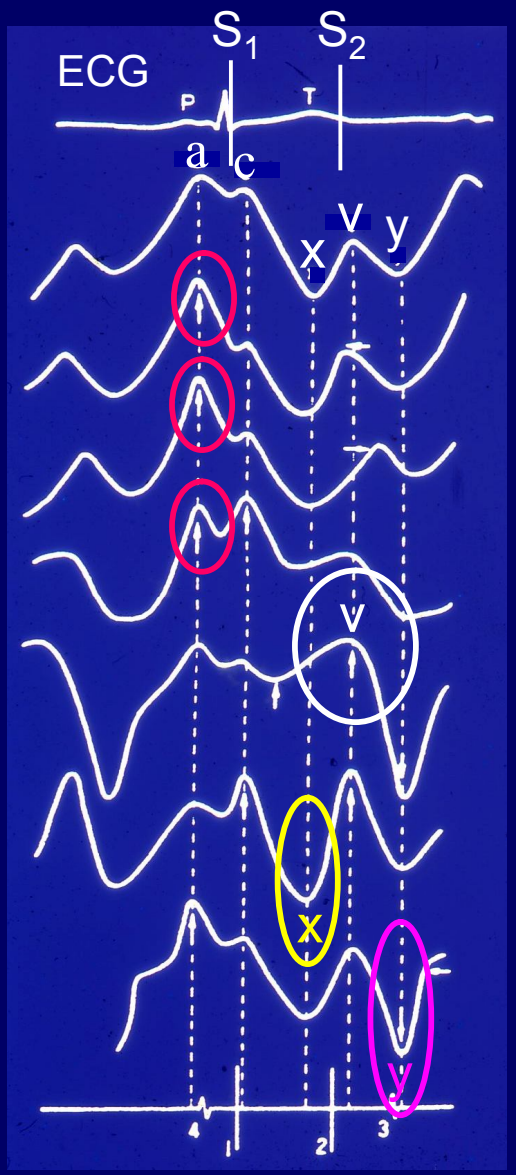
1) Jugular Venous pressure*
(height, top of pulsating venous column)
2) Wave forms – RA hemodynamic
3) Dysrhythmias
4) Patency of SVC

SVC
obstruction

External Jugular Vein

Not useful in hemodynamic/dysrhythmia evaluation
Usage of "no JVP" or "no JVD" (Misnormer)
misleading and in some case, illogical (e.g in hypovolemia)

RA Pressure Wave Forms



a – RA contraction; x – RA relaxation

v - RA filling; y – rapid RV filling

Normal

Pulmonary stenosis

Pulmonary hypertension

Prominent a wave
- Augmented RA Kick
(Increased resistance)

Functional
Increased RV compliance

Organic

Tricuspid stenosis

Tricuspid regurgitation

Prominent v wave
- Augmented RA filling

Cardiac tamponade – rapid decrease in pericardial following atrial systole

Chronic constrictive pericarditis – augmented filling in early diastole

1. Hemodynamic Pressure
2. Volumetric flow
3. Hemodynamic resistance
4. Compliance
5. Laplace law
6. Poiseuille's Law

Flow

- Systemic circulation - Cardiac output (Qs)
- Pulmonary circulation

  Pulmonary flow (Qp)

  - No shunt Qp = Qs
  - With shunts

    Left-to-right Qp/Qs > 1

    Right-to-left Qp/Qs < 1
- Coronary circulation

  $Qc = (ADP – LVDP)/Rc$

ADP = aortic diastolic pressure; LVDP = LV diastolic pressure
Rc = coronary artery resistance

Flow

Systemic circulation - Cardiac output (Qs)

$$Qs = \frac{O_2 \text{ consumption (cc/min)}}{Hb \times 13.6 \times (AO_t - MVB) \times 10}$$

Pulmonary circulation

$$Qp = \frac{O2 \text{ consumption (cc/min)}}{Hb \times 13.6 \times (PV - PA) \times 10}$$

$$Qp/Qs = \frac{(AO - MVB)}{(PV - PA)}$$

No shunt — Qp/Qs = 1 (Ao = PV; MVB = PA)

With shunts

- Left-to-right — Qp/Qs > 1
- Right-to-left — Qp/Qs < 1

1. Hemodynamic Pressure
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$$\text{Vessel Resistance} = \frac{\Delta \text{ pressure}}{\text{flow}}$$

Measurements

Systemic circulation

SVR = (mAo – RA)/CO

Pulmonary circulation

Pulm artery resistance = mPA/CO

Pulm arteriolar resistance = (mPA – PV)/CO

Units

Wood unit (mm Hg x min)/L

1 wood unit = 80 Dynes sec cm^{-5}

Coronary Circulation

Flow Qc = (ADP – LVDP)/Rc

Resistance to Coronary Blood Flow (Rc)

R_1. Epicardial conduit artery resistance

R_2. Dynamic intra-myocrdium resistance

Microcirculatory resistance arteries/arterioles

Autoregulation – increase flow up to 5X

R_3. Extravascular compressive resistance

Cardiac cycle time dependent

Time-varying reduction in flow driving pressure

Systole - Subendocardium pressure = LV pressure

Diastole - Subepicardium = near pleural pressure

Compressive effects - most prominent in subendocardium

$R_2 > R_3 >> R_1$ in normal heart

R_1 - significant, when diameter reduction > 50%, area > 75%

Epicardial Coronary Resistance (R_1)

Functional

Spasm

Organic

1) Intraluminal

Thrombus

2) Mural

Plaque, dissection

3) Extramural

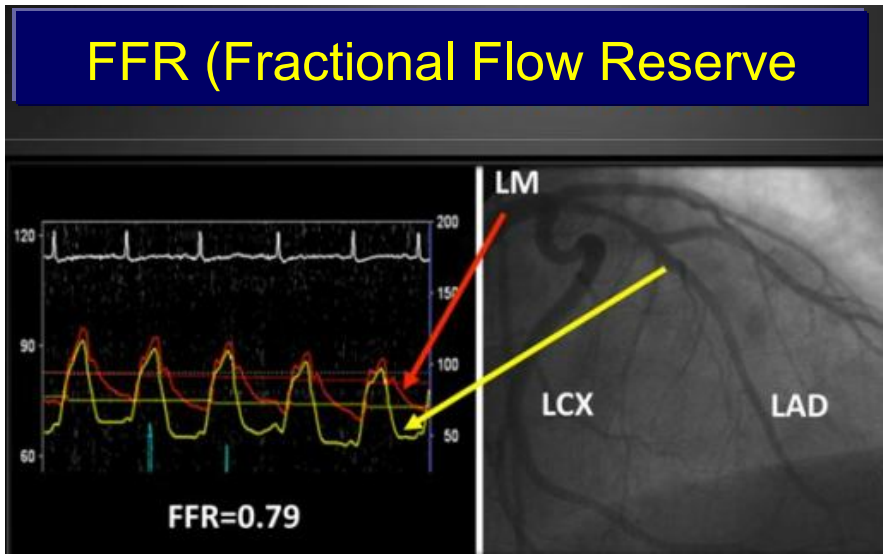
Myocardial bridging

Anomalous origin of coronary artery

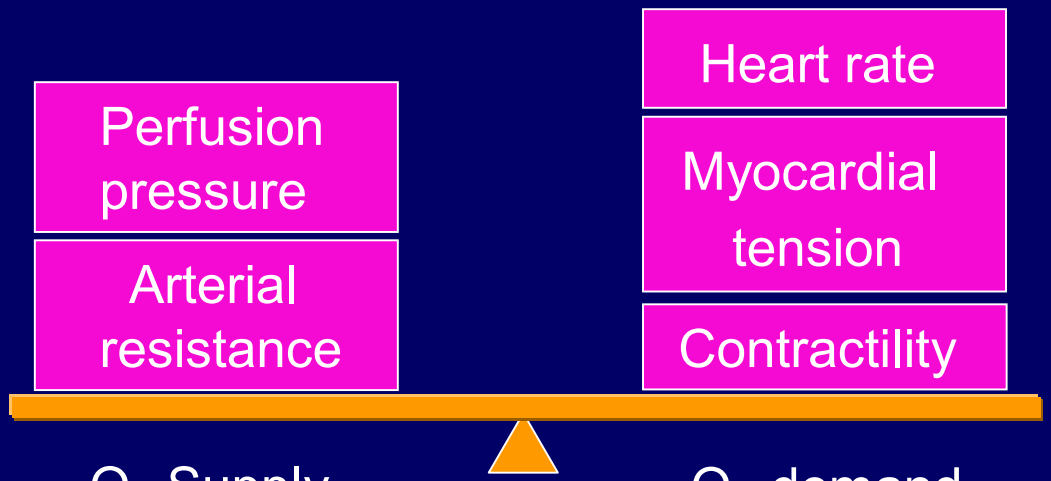
PA aneurysm, mediastinal fibrosis, neoplasm etc.

Resistance to Coronary Blood Flow

Occulostenotic reflex (見山攀山)
– No! No! (勿也! 勿也!)

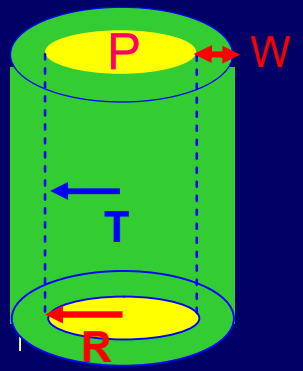


Myocardial Oxygen Economics
心肌氧氣經濟學



Laplace's Law

$T = P \times R / 2 \times W$



Coronary Flow (F) =
(ADP – LVDP)/Rc

O2 content (C) =
f (Hemoglobin, SaO2%

Clinical Index
Double Product
SBP x HR

T = tension
P = pressure
R = radius
W = wall thickness

心肌氧氣經濟學

冠狀動脈正常

血氧供、需平衡

供應增加　　需求增加

動用儲備流量

供、需平衡

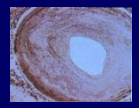
血流儲備量

冠狀動脈硬化

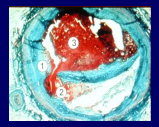
血氧供、需失衡 – 心肌缺血、缺氧

供應不足　　需求增加　　供應驟減

儲備流量不足



Spasm



需求不變

狹心症

心肌梗塞

心衰竭　　不整脈　　猝死

1. Hemodynamic Pressure
2. Volumetric flow
3. Hemodynamic resistance
4. Compliance
5. Laplace law
6. Poiseuille's Law

順應性 (Compliance)

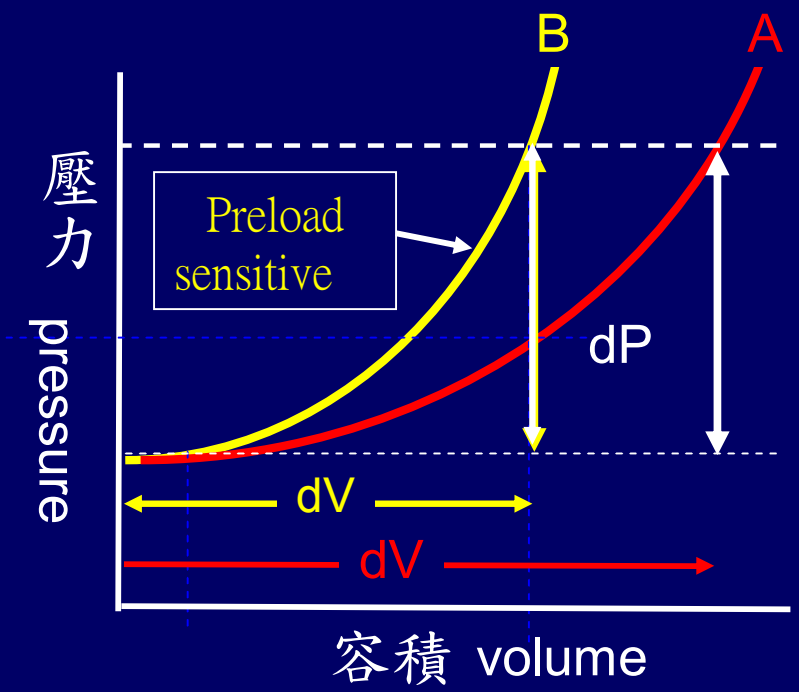
順應性 (C) 規範容積 (V) 壓力 (P) 間關係

$$C = dV/dP$$

[dV =容積變化; dP = 壓力變化]

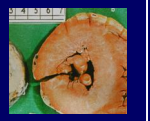
A — Compliant

B — Non-compliant



範例

- Bounding pulse in elderly
- LV diastolic dysfunction
- Stiff LV in concentric LVH



- Acute volume overload*
- Pericardial compressive syndrome
- Post-stenting balloon dilatation
- Stiff lungs in pulmonary edema

Pulse Pressure = f (stroke volume, arterial compliance)

C = dV/dP; dP = dV/C; dP = PP; dV = PP

PP = SV/C

脈壓 (pulse pressure, PP)

取決於心動容積 (stroke volume, SV) 與動脈順應性 (compliance, C)

動脈如果無阻塞或無嚴重收縮 – 脈壓反映脈搏大小

Pulse pressure	Pulse	PP = SV/C
30 – 50 mmHg	normal	normal SV and C
	*"normal (pseudo)"	↓ SV; ↓ C
< 30 mmHg	weak	↓ SV; normal C
➢50 mmHg	bounding	↑ SV; normal C
		normal SV; ↓ C

*Beware of pitfall

Bounding Pulse

$$PP = \frac{SV}{C}$$

1) Increased Left ventricular (LV) SV
   - High output status (LV SV = effective SV)
     - Physiologic – exercise, anxiety, pregnancy
     - Pathologic – fever, hyperthyroidism, severe anemia
       - Paget
   - Run-off to low-resistance system (LVSV > effective SV)
     1) LV (severe AR) ;
     2) Right heart (rupture sinus of Valsalva);
     3) PA (PDA, AP window);
     4) Systemi vein (AV shunts)

2) Decrease artrerial compliance
   - Atherosclerosis (elderly)

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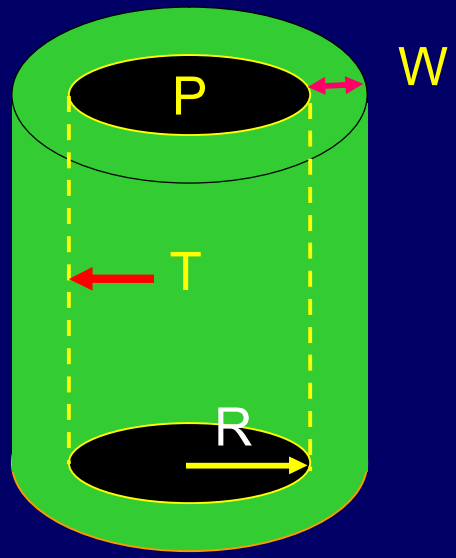
Laplace Law

$$T = \frac{P \times R}{2 \times W}$$



T = tension
P = pressure
R = radius
W = wall thickness

範例

Myocardial O_2 consumption = f (HR, wall tension, contractility)

LV pressure overload (HTN, AS) – 求心性肥厚(concentric)
increased P and W

LV volume overload – 遠心性肥厚 (eccentric) – increased R

1. Hemodynamic Pressure
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Poiseuille's Law

$$\dot{Q} = \frac{\Delta P \pi \gamma^4}{8L\mu}$$

$$R = \frac{\Delta P}{\dot{Q}} = \frac{8L\mu}{\pi \gamma^4}$$

$\dot{Q}$ = flow per unit time

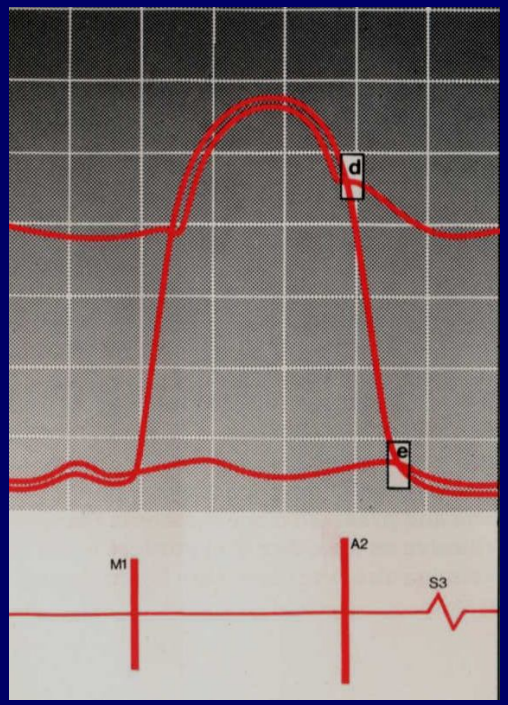
ΔP = pressure gradient

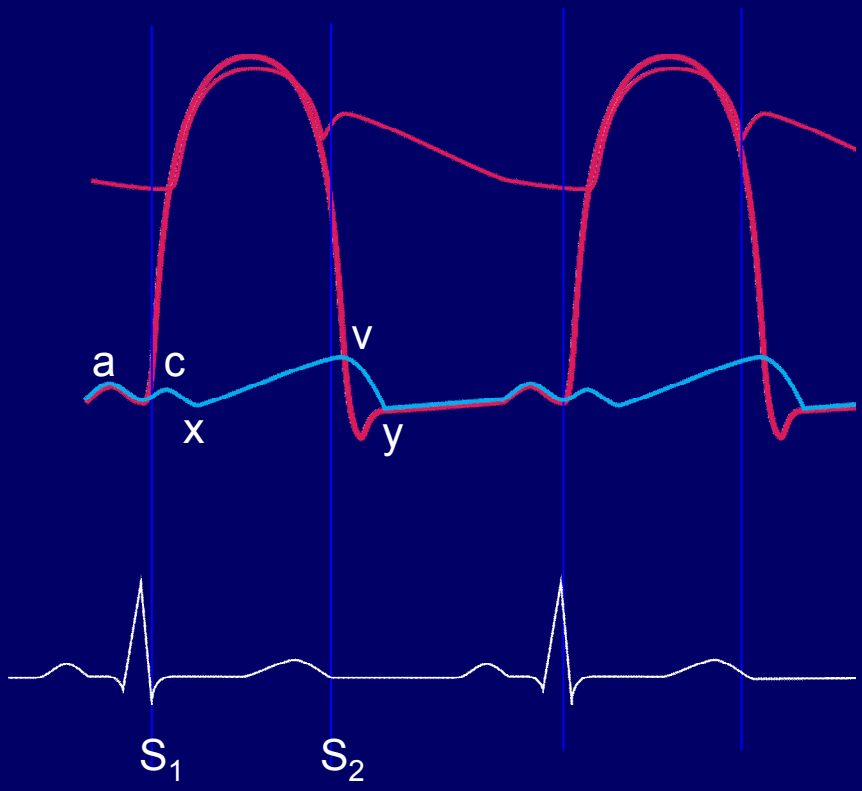
γ = tube radius

L = length of tube

μ = viscosity

Cardiac Cycle

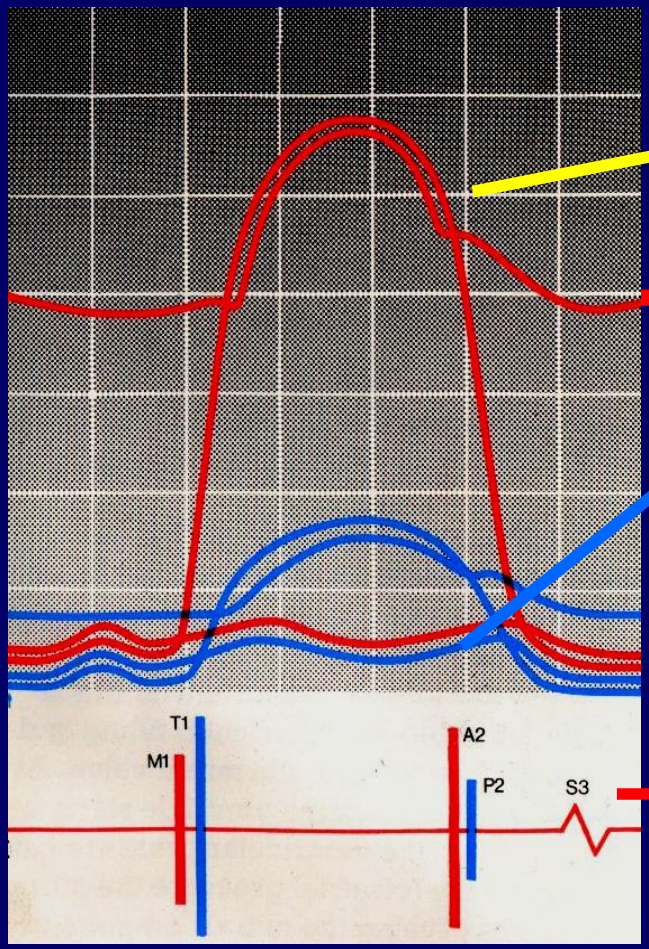


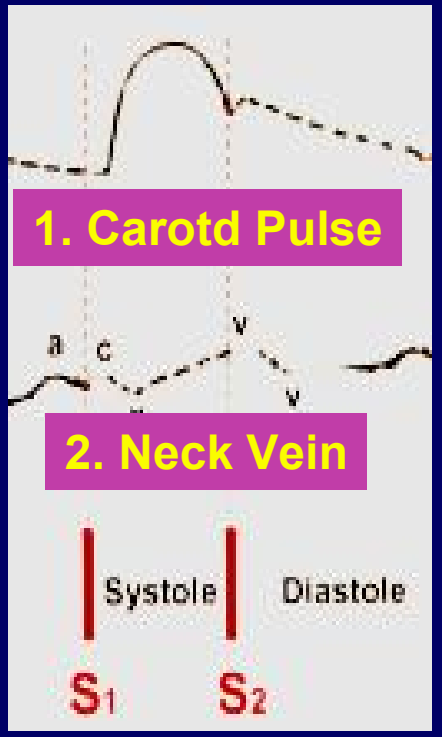


a – atrial contraction;
c – annulus upward motion;
x – atrial relaxation;
v - atrial filling
y – rapid ventricular filling

PE in Hemodynamic Assessments

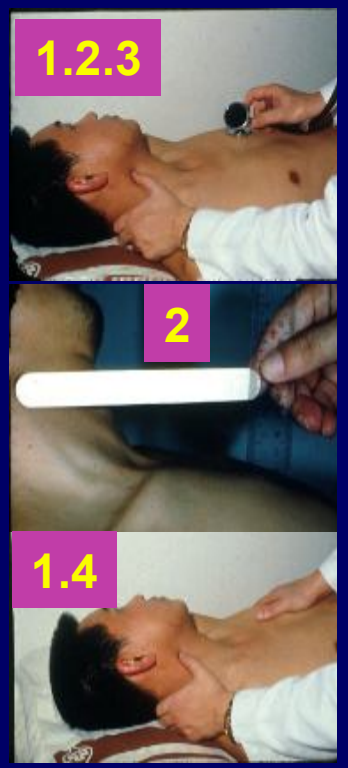
Cardiac Physiology ⟷ **Physical Examination**





1. Carotd Pulse
2. Neck Vein
3. Sounds
4. motions

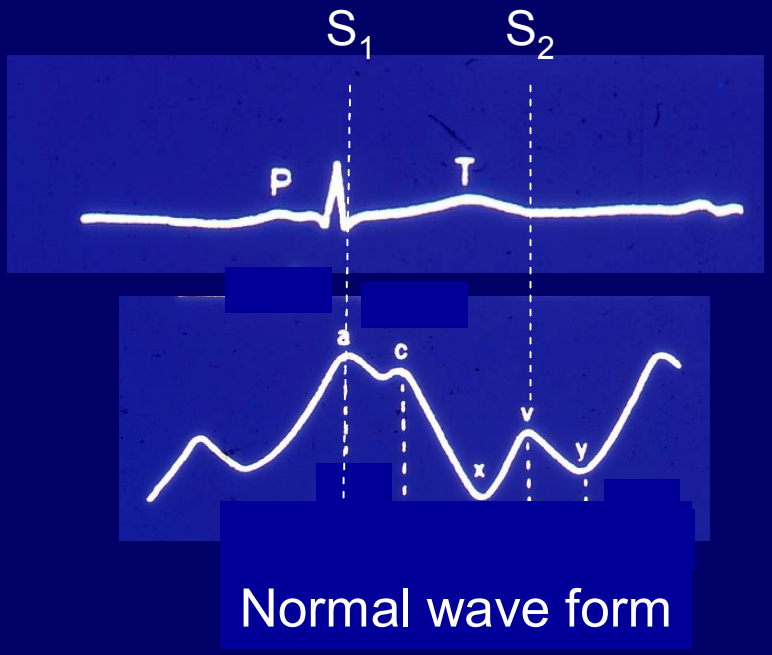
Integrated Exams



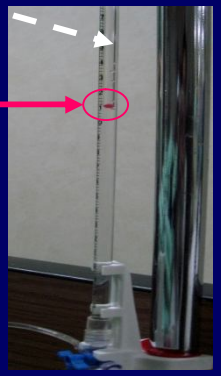
Internal Jugular Venous Pressure*

– CVP line by mother nature

Venous wave forms
Similar to RA, but with time-lag



Normal wave form



(3 in 1 Exam)

*Most useful in clinical calibration

Valvular Aortic Stenosis

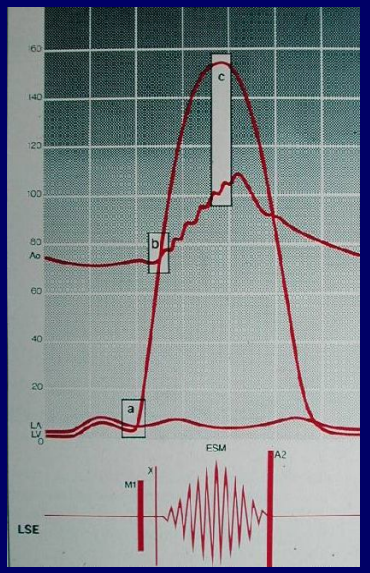
Clinical presentations

CHF

Syncope

Angina

Sudden death



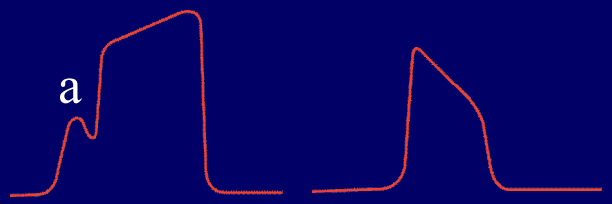
S_4 S_1 S_2

Carotid pulse

Pulsus tardus et parvus

Apical impulse

localized, sustained



Chronic pressure overload

Concentric hypertrophy

Decreased LV compliance

Coronary Perfusion

Increased wall tension

Decreased perfusion pressire

Microvascular dysfunction

S_4 – atrial kick

Left Mastectomy