Applied Physiology and Hemodynamics

洪瑞松

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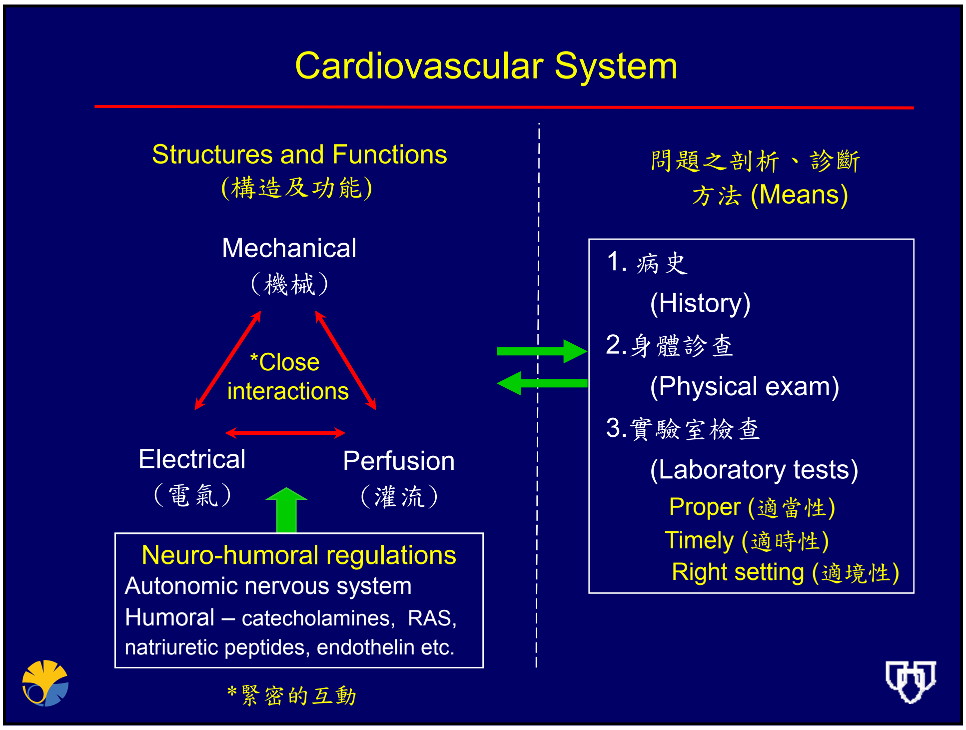
2012. 3. 10



Cardiovascular System

Structures and Functions
(構造及功能)

Mechanical
（機械）

*Close
interactions

Electrical
（電氣）

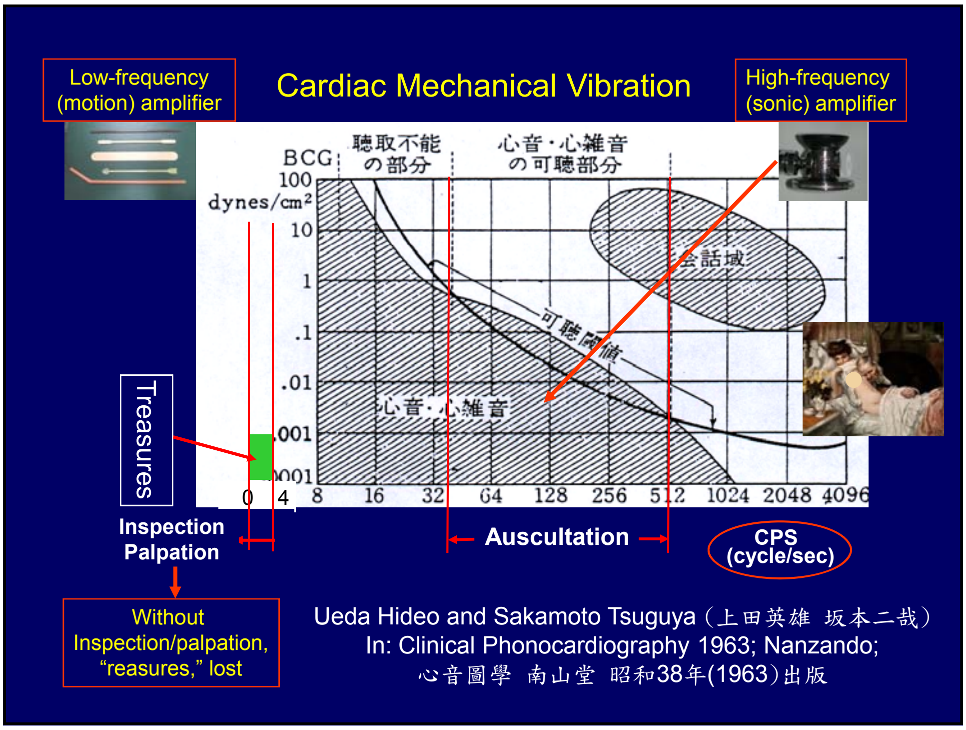
Perfusion
（灌流）

Neuro-humoral regulations
Autonomic nervous system
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)
Right setting (適境性)



Low-frequency (motion) amplifier

Cardiac Mechanical Vibration

High-frequency (sonic) amplifier

Treasures

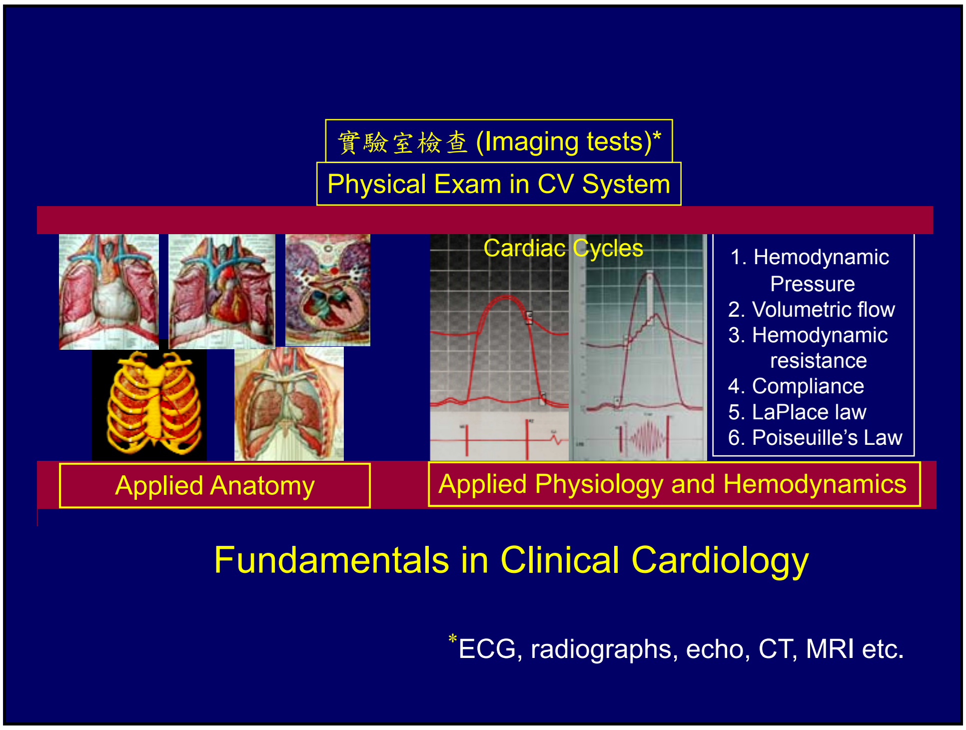
Inspection
Palpation

Auscultation

CPS
(cycle/sec)

Without Inspection/palpation, “reasures,” lost

Ueda Hideo and Sakamoto Tsuguya（上田英雄 坂本二哉）
In: Clinical Phonocardiography 1963; Nanzando;
心音圖學 南山堂 昭和38年(1963)出版



實驗室檢查 (Imaging tests)*

Physical Exam in CV System

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

Applied Anatomy

Applied Physiology and Hemodynamics

Fundamentals in Clinical Cardiology

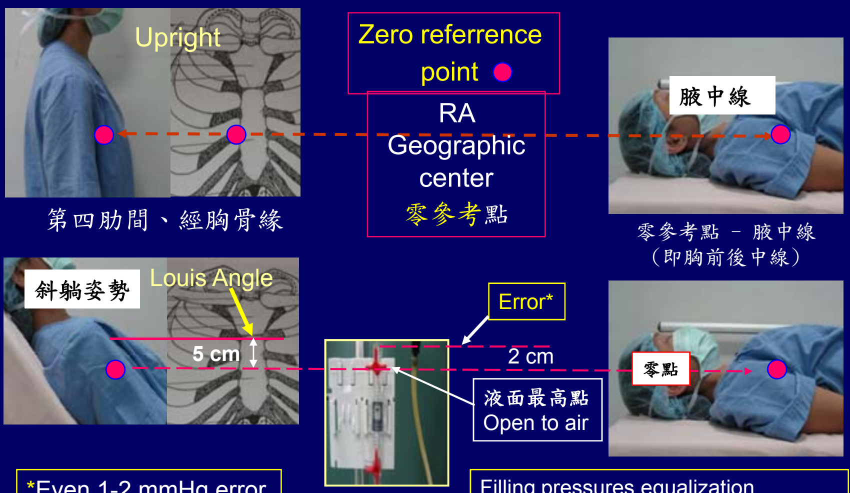
*ECG, radiographs, echo, CT, MRI etc.

Applied Physiology and Hemodynamics

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

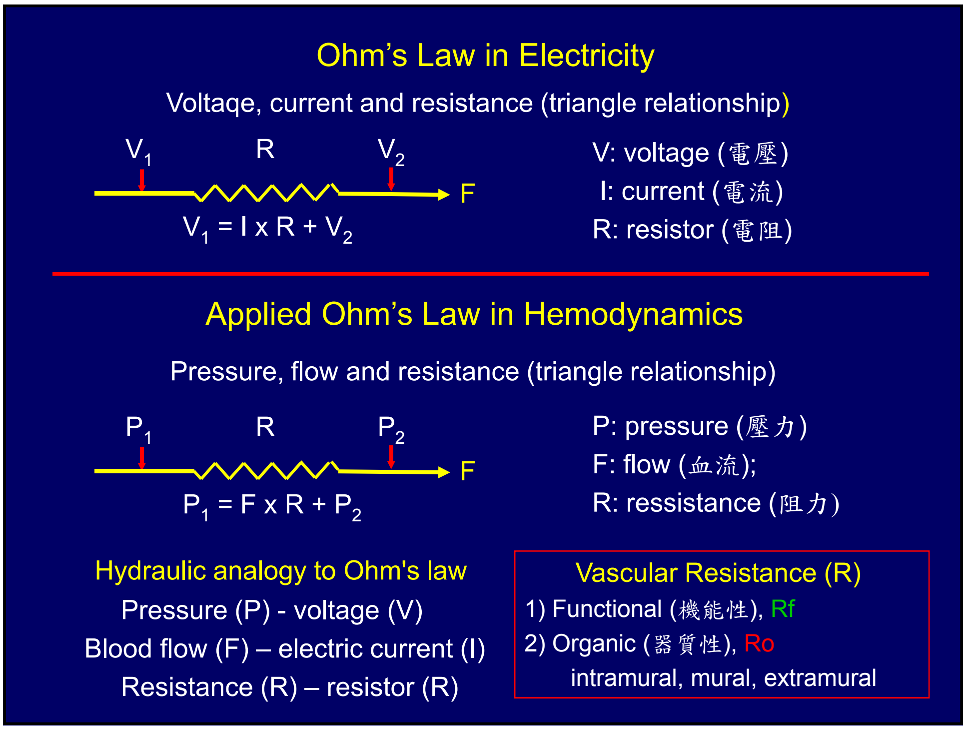
Hemodynamic Pressure – Transducer Calibration

Relative to Atmospheric Pressure



*Even 1-2 mmHg error may have significant impact

Filling pressures equalization
Pericardial compression syndrome
Low-pressure gradient – MS, TS
ASD closure



Ohm's Law in Electricity

Voltaqe, current and resistance (triangle relationship)

$V_1 = I \times R + V_2$

V: voltage (電壓)
I: current (電流)
R: resistor (電阻)

Applied Ohm's Law in Hemodynamics

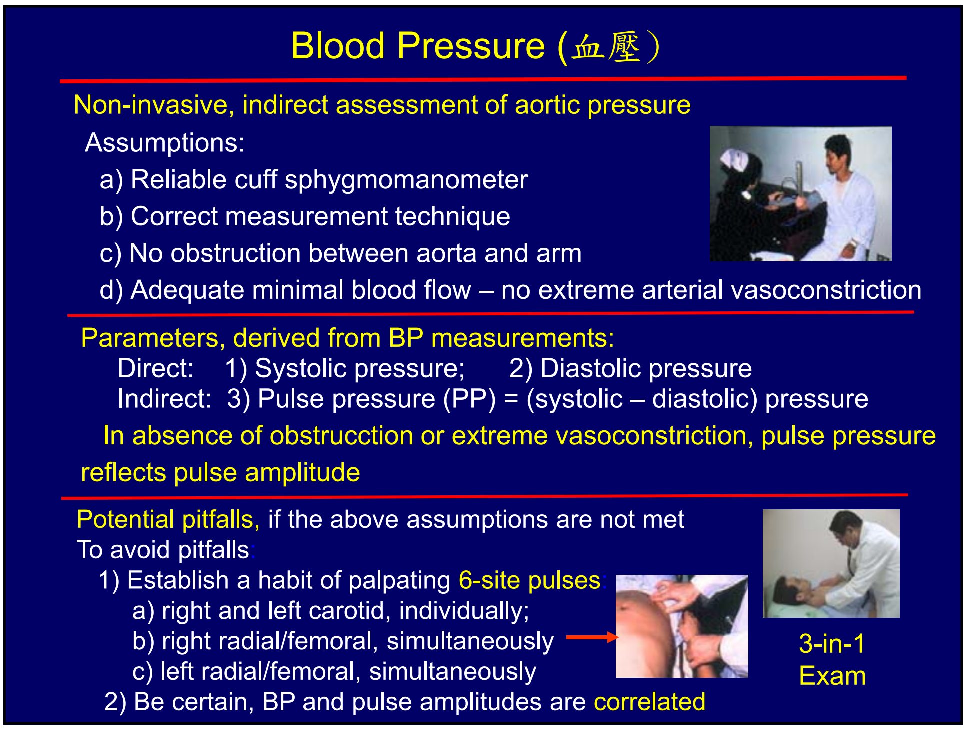
Pressure, flow and resistance (triangle relationship)

$P_1 = F \times R + P_2$

P: pressure (壓力)
F: flow (血流);
R: ressistance (阻力)

Hydraulic analogy to Ohm's law
Pressure (P) - voltage (V)
Blood flow (F) – electric current (I)
Resistance (R) – resistor (R)

Vascular Resistance (R)
1) Functional (機能性), Rf
2) Organic (器質性), Ro
intramural, mural, extramural



Blood Pressure (血壓)

Non-invasive, indirect assessment of aortic pressure

Assumptions:
- a) Reliable cuff sphygmomanometer
- b) Correct measurement technique
- c) No obstruction between aorta and arm
- d) Adequate minimal blood flow – no extreme arterial vasoconstriction

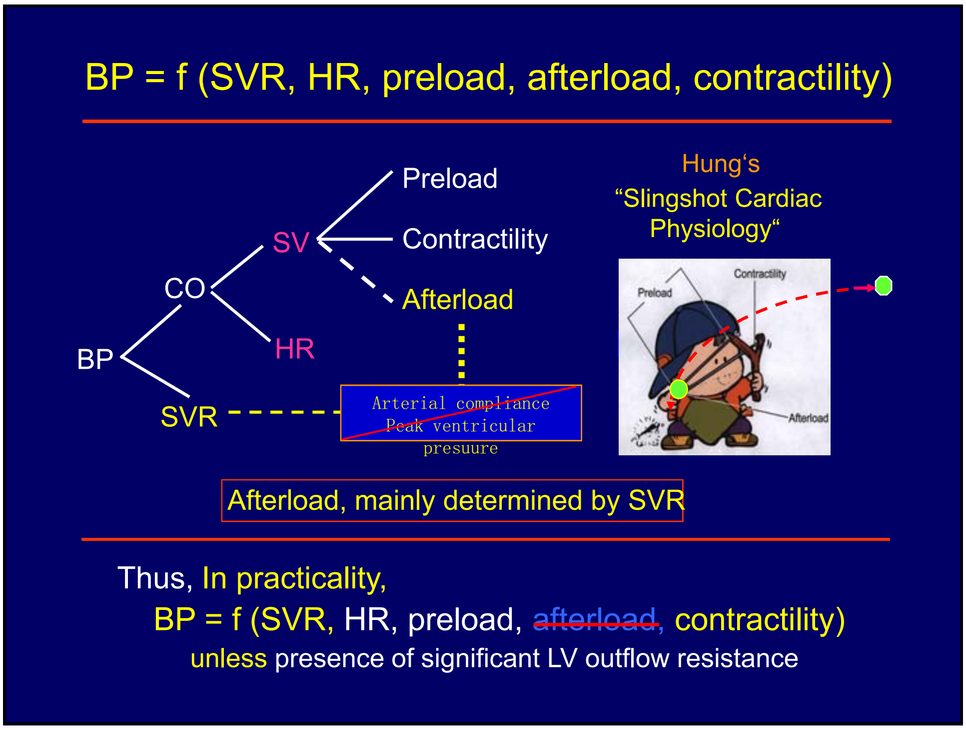
Parameters, derived from BP measurements:
Direct: 1) Systolic pressure; 2) Diastolic pressure
Indirect: 3) Pulse pressure (PP) = (systolic – diastolic) pressure

In absence of obstrucction or extreme vasoconstriction, pulse pressure reflects pulse amplitude

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

3-in-1
Exam



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

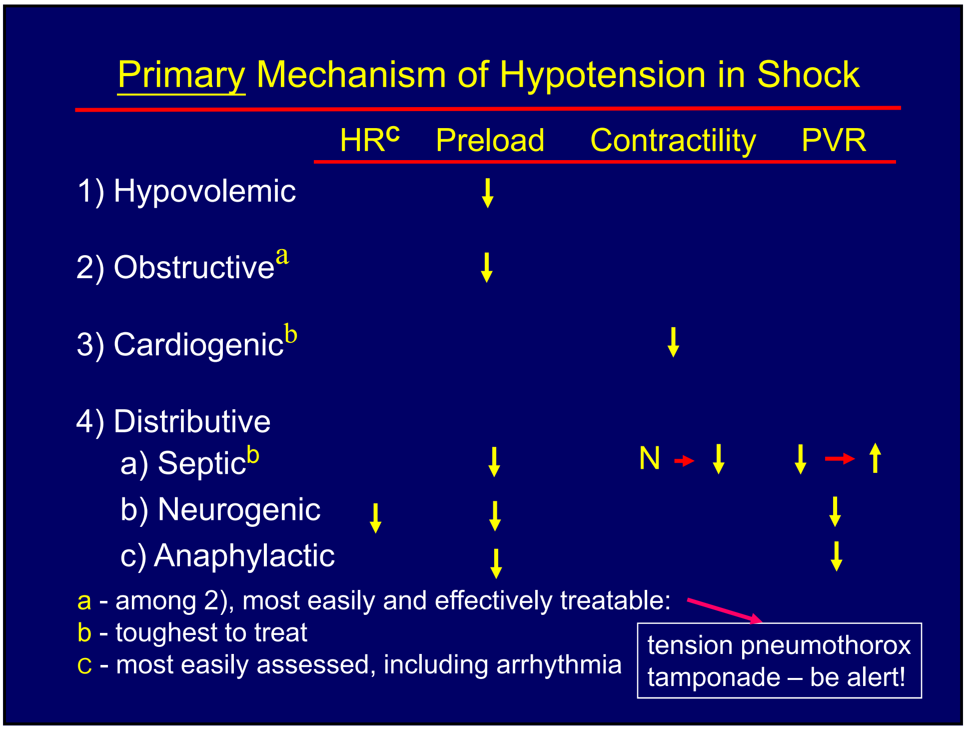
Hung's "Slingshot Cardiac Physiology"

Afterload, mainly determined by SVR

Thus, In practicality,

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

unless presence of significant LV outflow resistance

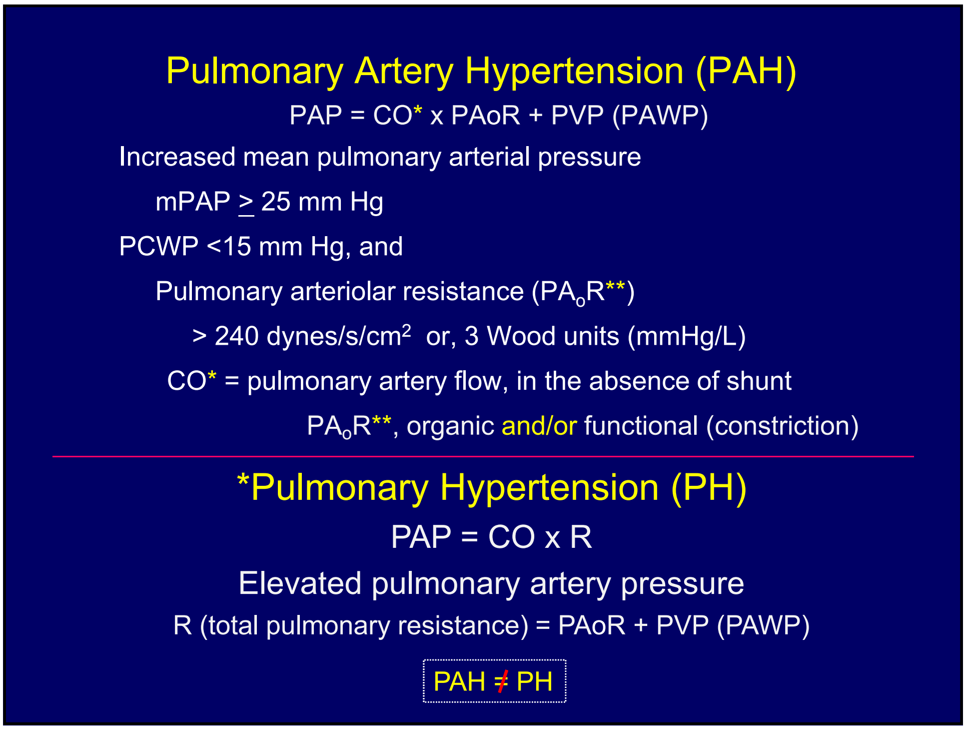


Primary Mechanism of Hypotension in Shock

	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)

PAP = CO* x PAoR + PVP (PAWP)

Increased mean pulmonary arterial pressure

mPAP $\geq$ 25 mm Hg

PCWP <15 mm Hg, and

Pulmonary arteriolar resistance (PA$_o$R**)

> 240 dynes/s/cm^2 or, 3 Wood units (mmHg/L)

CO* = pulmonary artery flow, in the absence of shunt

PA$_o$R**, organic and/or functional (constriction)

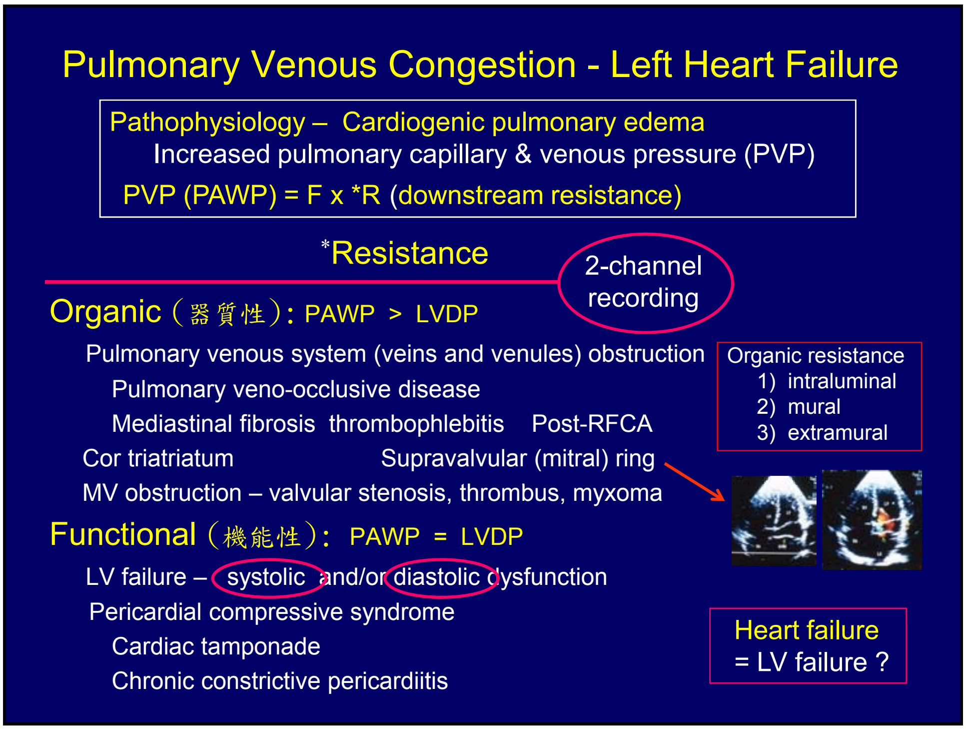
*Pulmonary Hypertension (PH)

PAP = CO x R

Elevated pulmonary artery pressure

R (total pulmonary resistance) = PAoR + PVP (PAWP)

PAH ≠ PH



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

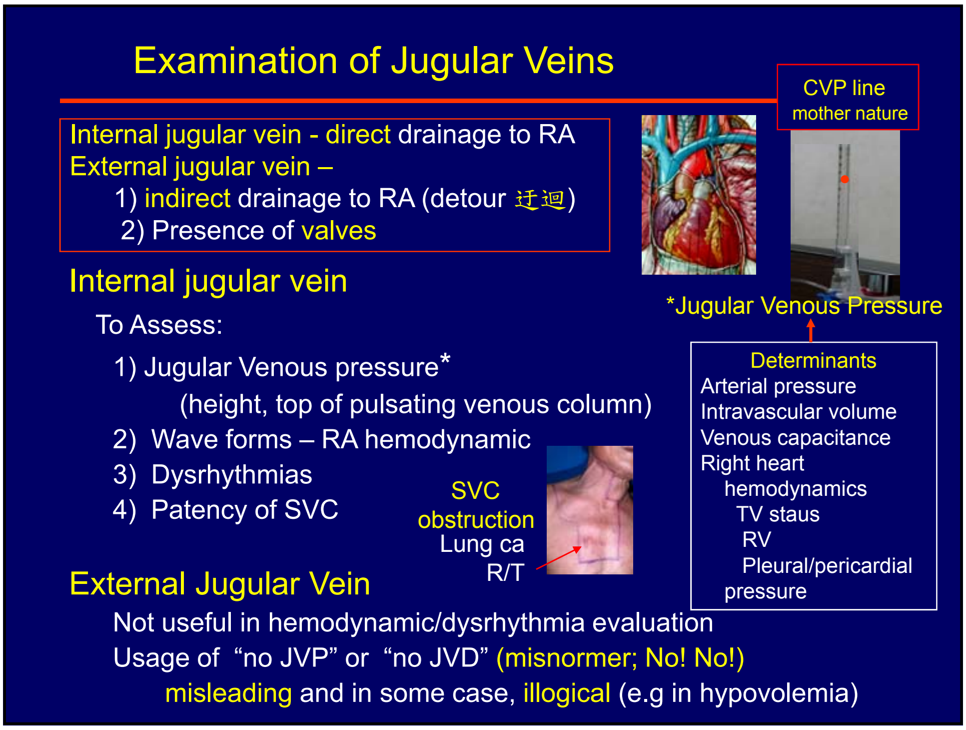
Pulmonary venous system (veins and venules) obstruction
  Pulmonary veno-occlusive disease
  Mediastinal fibrosis thrombophlebitis Post-RFCA
Cor triatriatum Supravalvular (mitral) ring
MV obstruction – valvular stenosis, thrombus, myxoma

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

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

Internal jugular vein

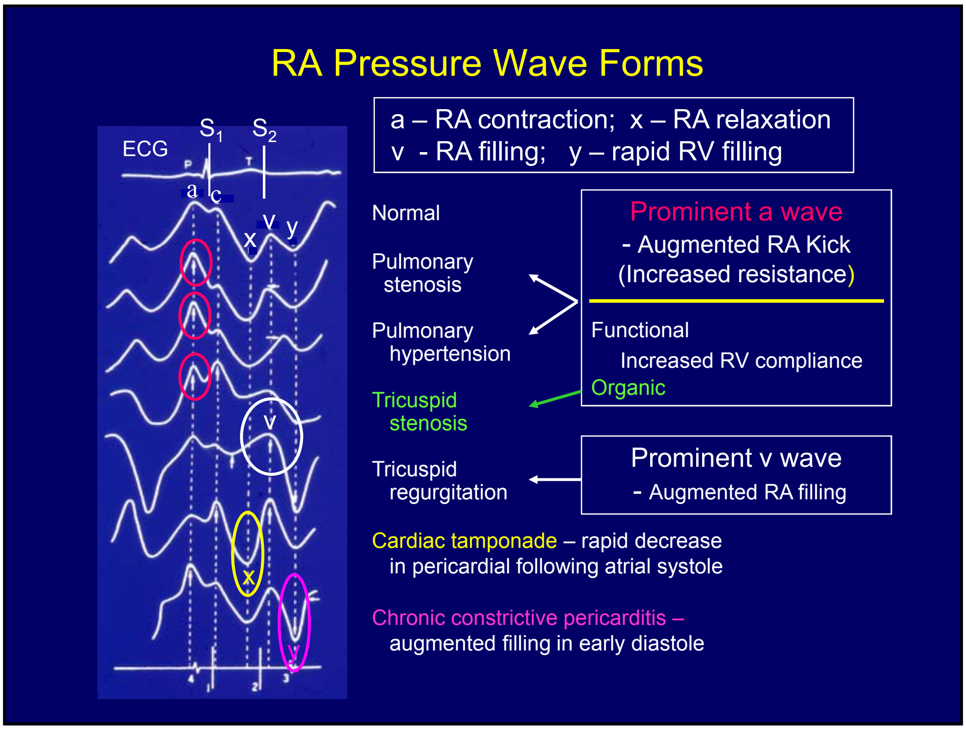
To Assess:

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

SVC
obstruction
Lung ca
R/T

External Jugular Vein

Not useful in hemodynamic/dysrhythmia evaluation
Usage of “no JVP” or “no JVD” (misnormer; No! No!)
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

Tricuspid
stenosis

Tricuspid
regurgitation

Prominent a wave
- Augmented RA Kick
(Increased resistance)

Functional
Increased RV compliance
Organic

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

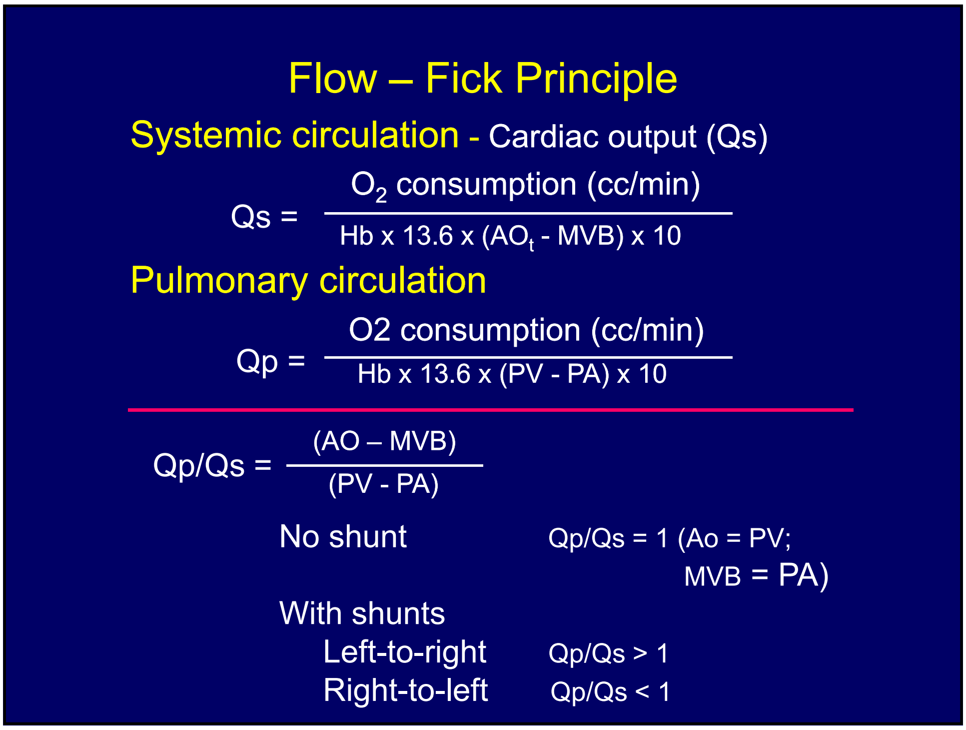
  Pulmonary flow (Qp)
  - No shunt Qp = Qs
  - With shunts

    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 – Fick Principle

Systemic circulation - Cardiac output (Qs)

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

Pulmonary circulation

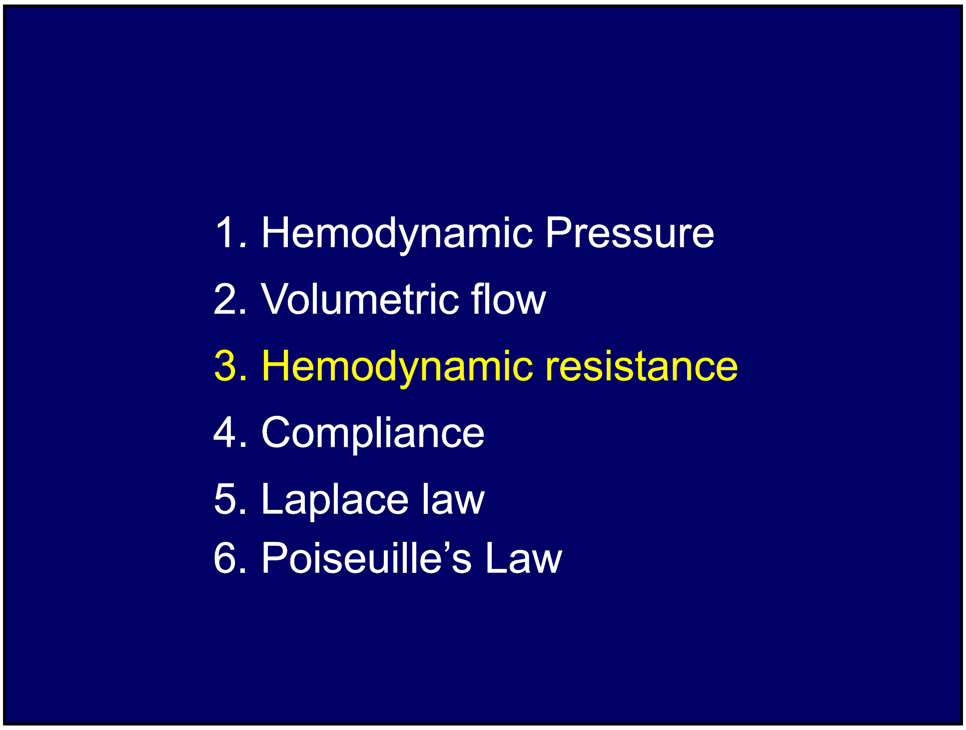
$$Qp = \frac{\text{O2 consumption (cc/min)}}{\text{Hb x 13.6 x (PV - PA) x 10}}$$

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

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

With shunts

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



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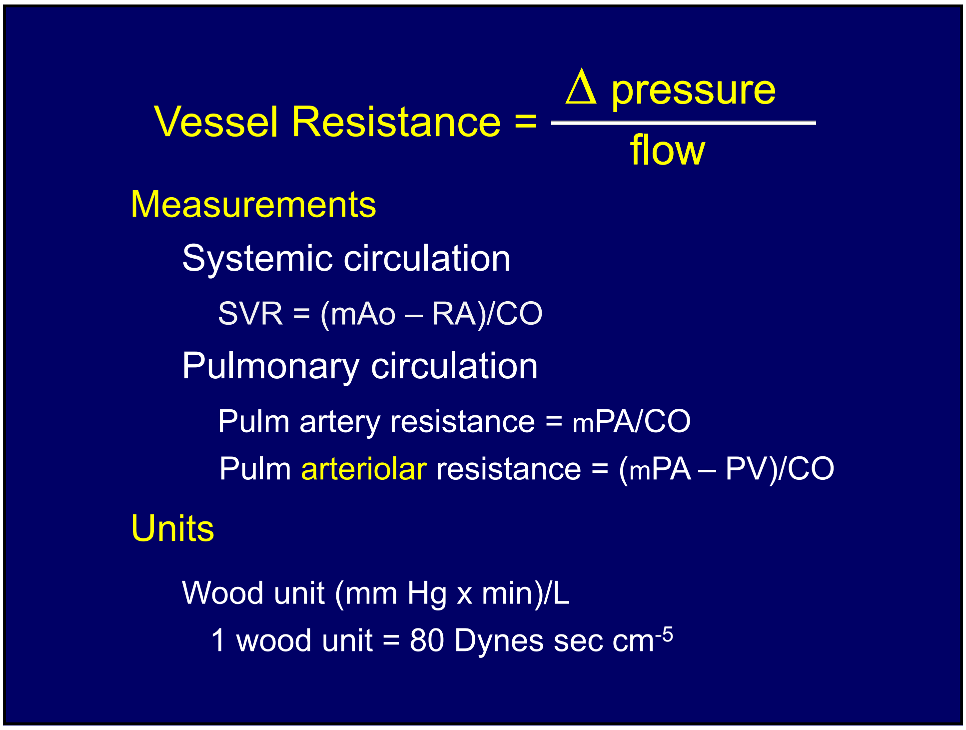


$$\text{Vessel Resistance} = \frac{\Delta \text{ pressure}}{\text{flow}}$$

Measurements

Systemic circulation

SVR = (mAo – RA)/CO

Pulmonary circulation

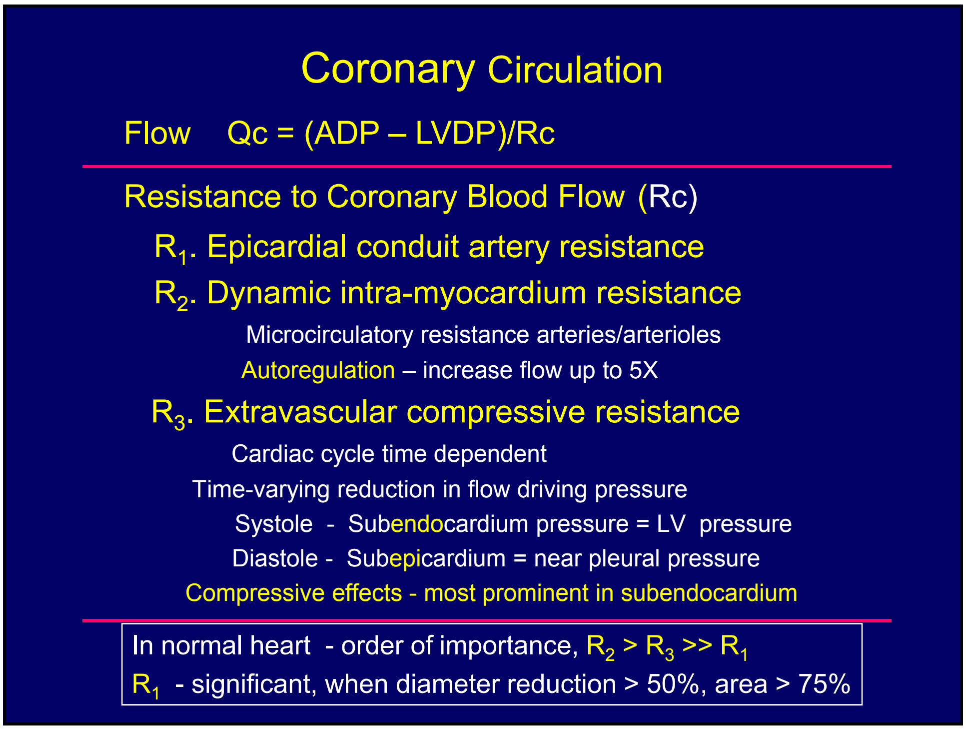
Pulm artery resistance = mPA/CO

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-myocardium 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

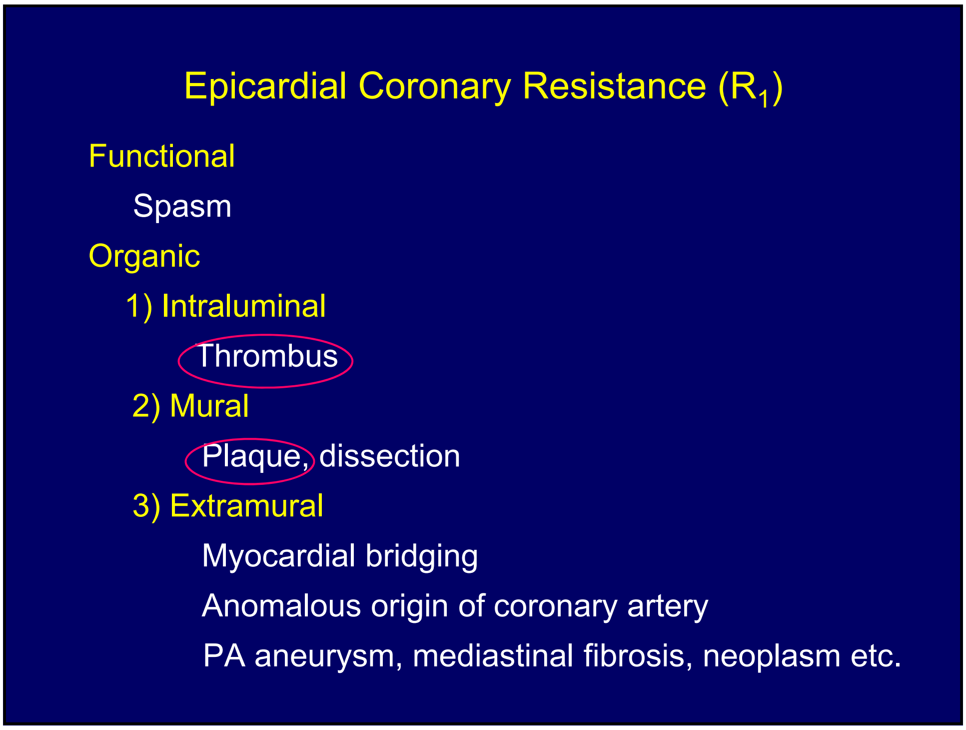
Systole - Subendocardium pressure = LV pressure

Diastole - Subepicardium = near pleural pressure

Compressive effects - most prominent in subendocardium

In normal heart - order of importance, $R_2 > R_3 >> R_1$

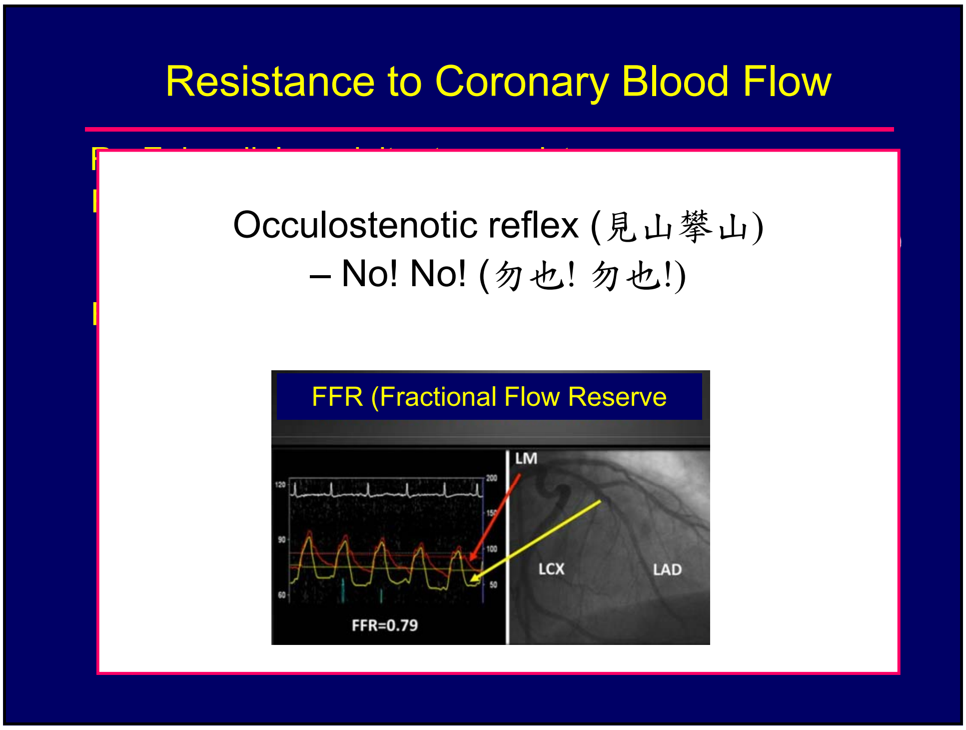
R_1 - significant, when diameter reduction > 50%, area > 75%



Epicardial Coronary Resistance (R_1)

Functional
- Spasm

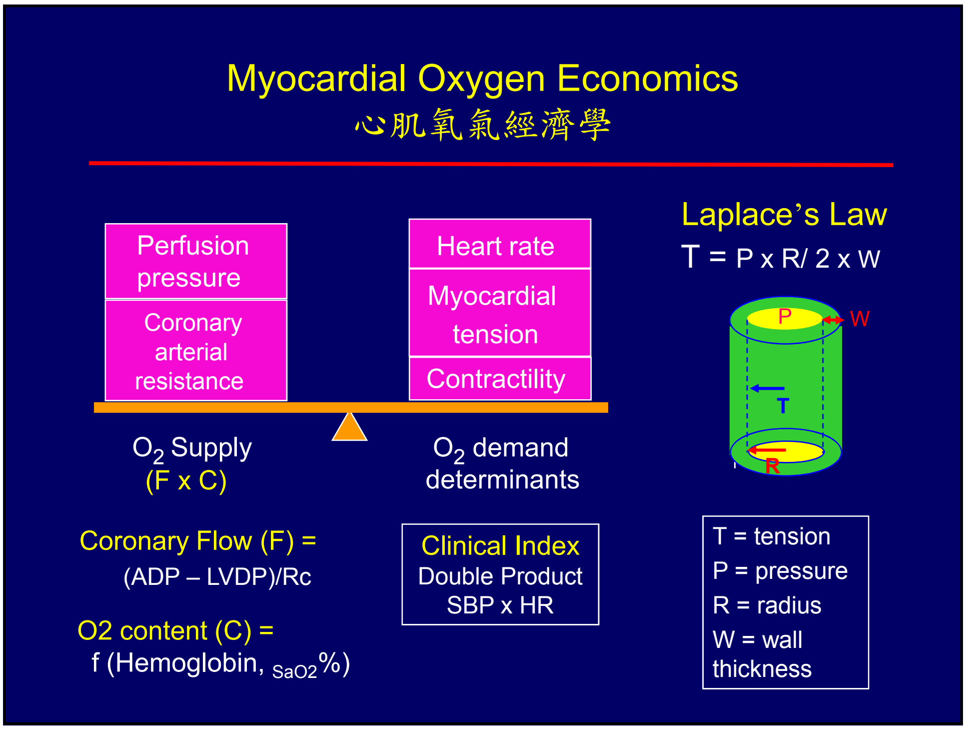
Organic
- 1) Intraluminal
  - Thrombus
- 2) Mural
  - Plaque, dissection
- 3) Extramural
  - Myocardial bridging
  - Anomalous origin of coronary artery
  - PA aneurysm, mediastinal fibrosis, neoplasm etc.



Resistance to Coronary Blood Flow

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

FFR (Fractional Flow Reserve



Myocardial Oxygen Economics
心肌氧氣經濟學

Perfusion pressure

Coronary arterial resistance

Heart rate

Myocardial tension

Contractility

O_2 Supply
(F x C)

O_2 demand
determinants

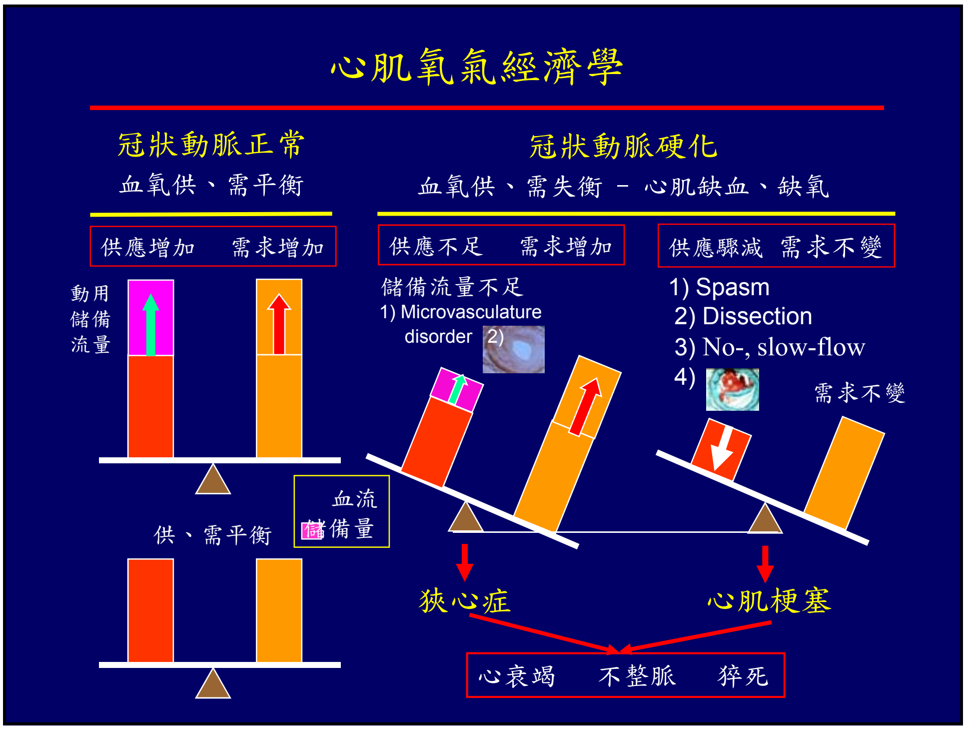
Laplace's Law
T = P x R/ 2 x W

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

儲備流量不足
1) Microvasculature disorder
2)

供應驟減　需求不變

1) Spasm
2) Dissection
3) No-, slow-flow
4)

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

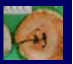
順應性 (Compliance)

順應性 (C) 規範容積 (V) 壓力 (P) 間關係

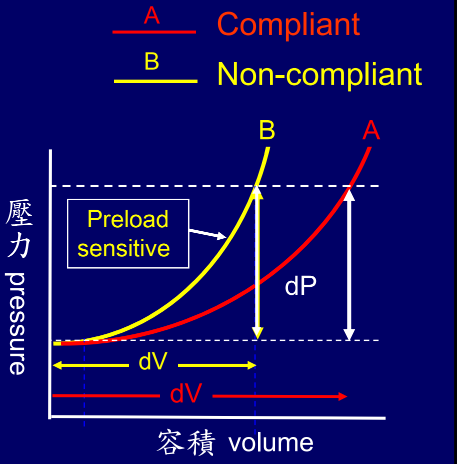
$$C = dV/dP$$

[dV =容積變化; dP = 壓力變化]

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)

**In absence of obstruction or extreme vasoconstriction, pulse pressure (PP) reflects pulse amplitude

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

**Not applicable during IABP use

*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) Systemic vein (AV shunts)

2) Decrease arterial compliance

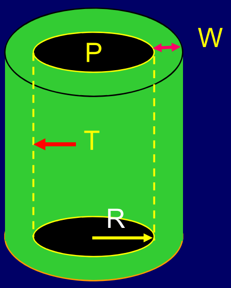
Atherosclerosis (elderly)

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

Laplace Law

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

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



Appplication Examples (範例)

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

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

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

1. Hemodynamic Pressure
2. Volumetric flow
3. Hemodynamic resistance
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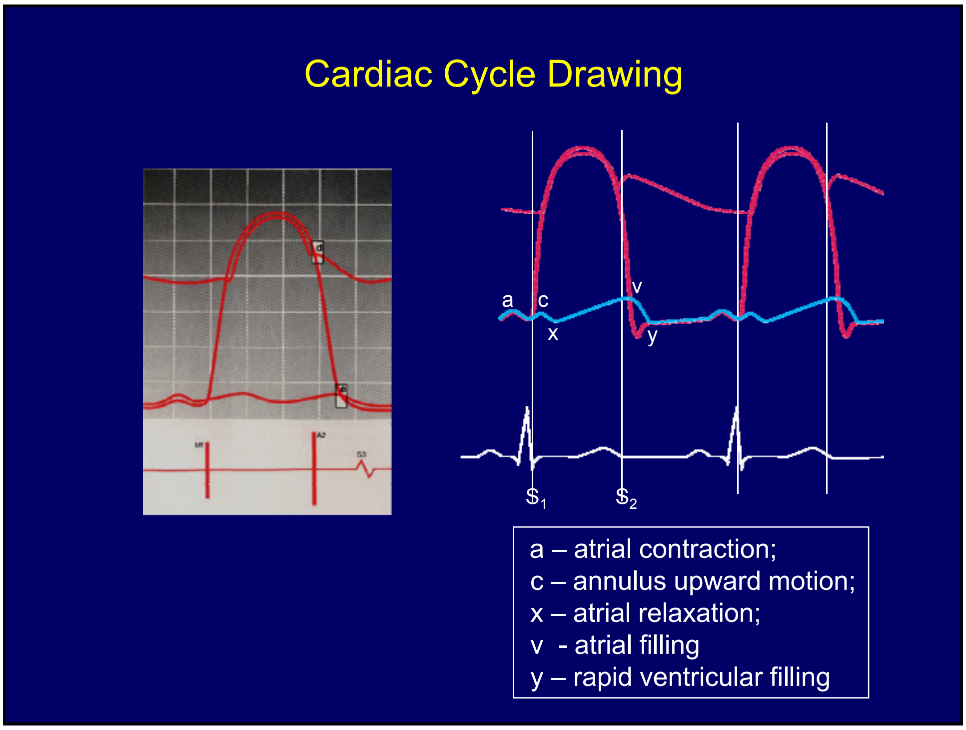
6. Poiseuille's Law

Poiseuille's Law

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

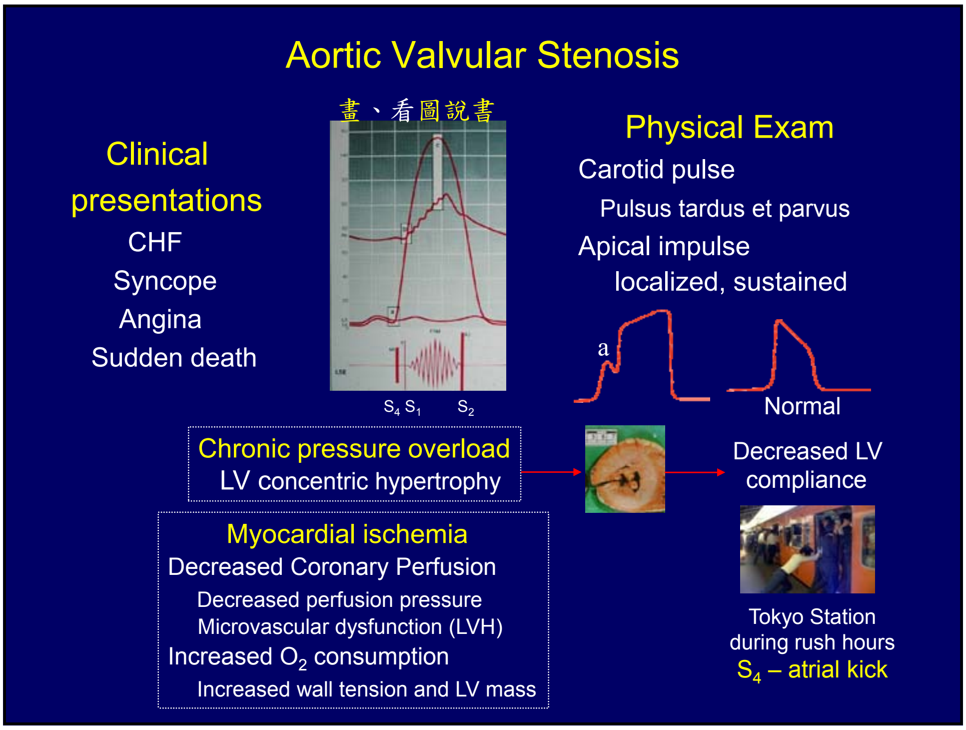
$\dot{Q}$ = flow per unit time
ΔP = pressure gradient
γ = tube radius
L = length of tube
μ = viscosity

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



Cardiac Cycle Drawing

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



Aortic Valvular Stenosis

畫、看圖說書

Clinical presentations
- CHF
- Syncope
- Angina
- Sudden death

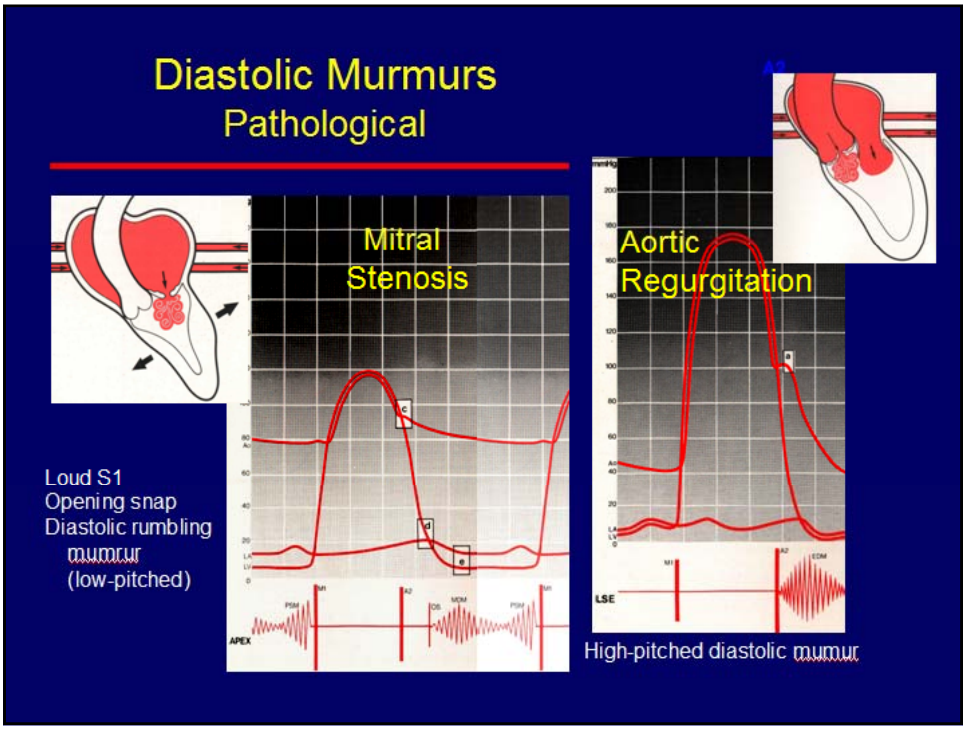
Physical Exam
- Carotid pulse
  - Pulsus tardus et parvus
- Apical impulse
  - localized, sustained

Chronic pressure overload
LV concentric hypertrophy

Decreased LV compliance

Myocardial ischemia
- Decreased Coronary Perfusion
  - Decreased perfusion pressure
  - Microvascular dysfunction (LVH)
- Increased O_2 consumption
  - Increased wall tension and LV mass

Tokyo Station during rush hours
S_4 – atrial kick



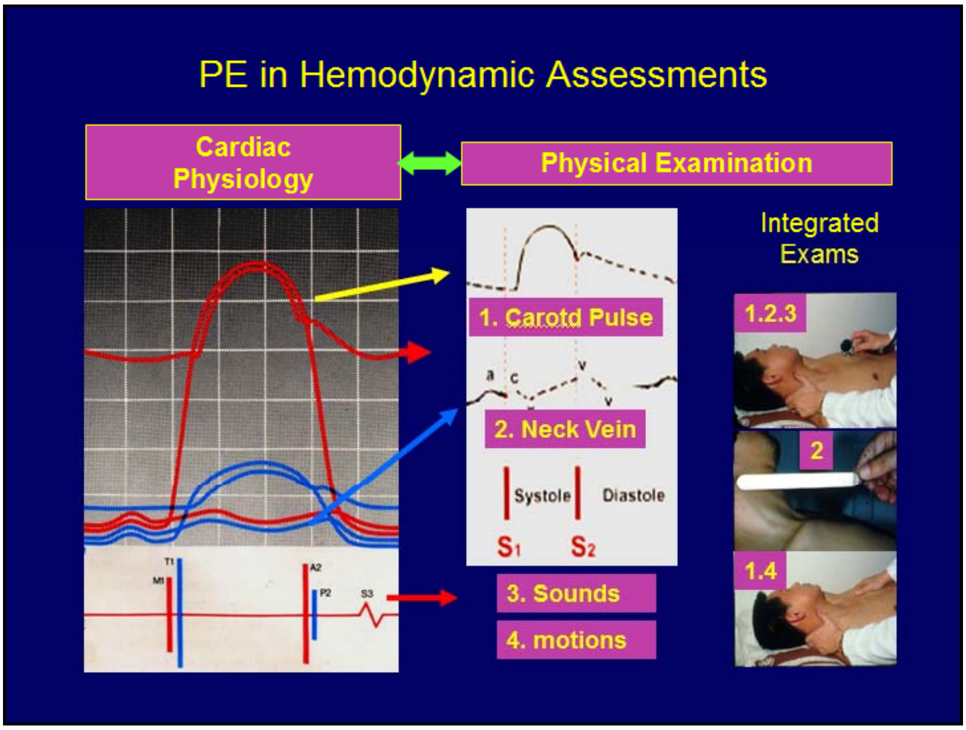
Diastolic Murmurs
Pathological

Mitral Stenosis

Aortic Regurgitation

Loud S1
Opening snap
Diastolic rumbling mumrur (low-pitched)

High-pitched diastolic mumur



PE in Hemodynamic Assessments

Cardiac Physiology

Physical Examination

Integrated Exams

1. Carotd Pulse

2. Neck Vein

Systole
Diastole
S_1 S_2

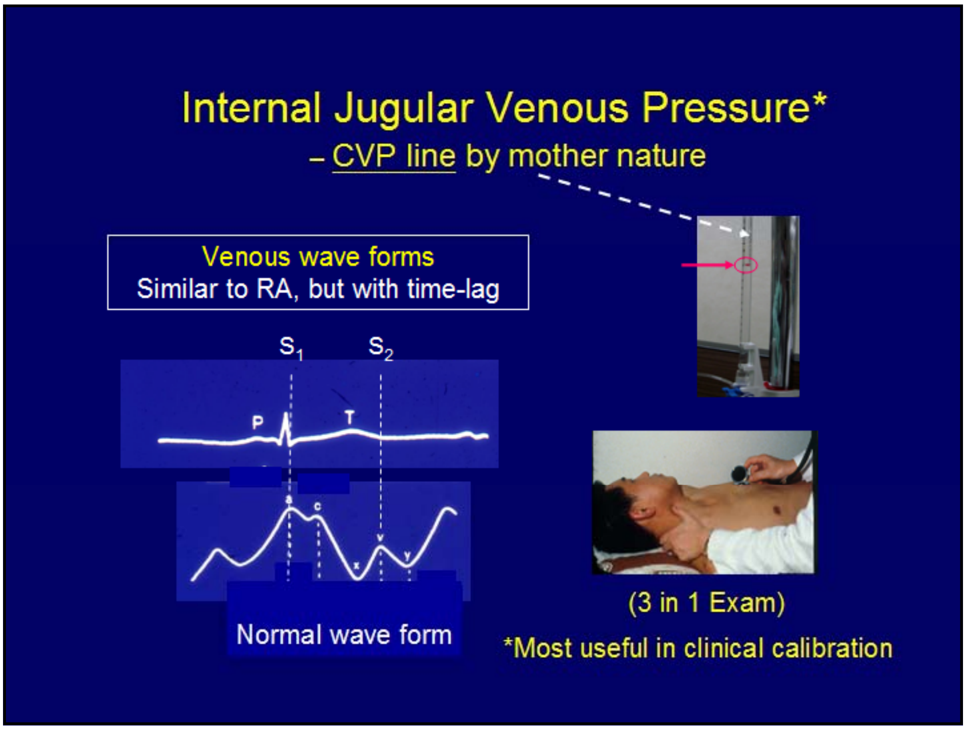
3. Sounds

4. motions

1.2.3

2

1.4



Internal Jugular Venous Pressure*

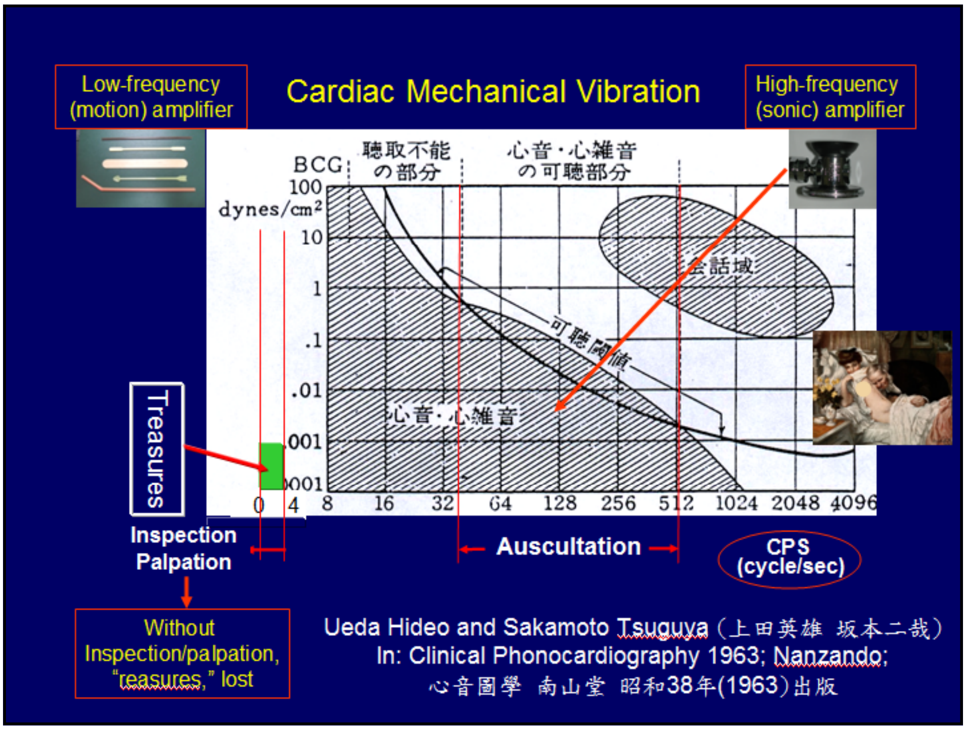
– CVP line by mother nature

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

Normal wave form

(3 in 1 Exam)

*Most useful in clinical calibration



Cardiac Mechanical Vibration

Low-frequency (motion) amplifier

High-frequency (sonic) amplifier

Inspection
Palpation

Auscultation

CPS
(cycle/sec)

Without
Inspection/palpation,
“reasures,” lost

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