Principles of Haemodynamics

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SR CARDIOLOGY

Overview

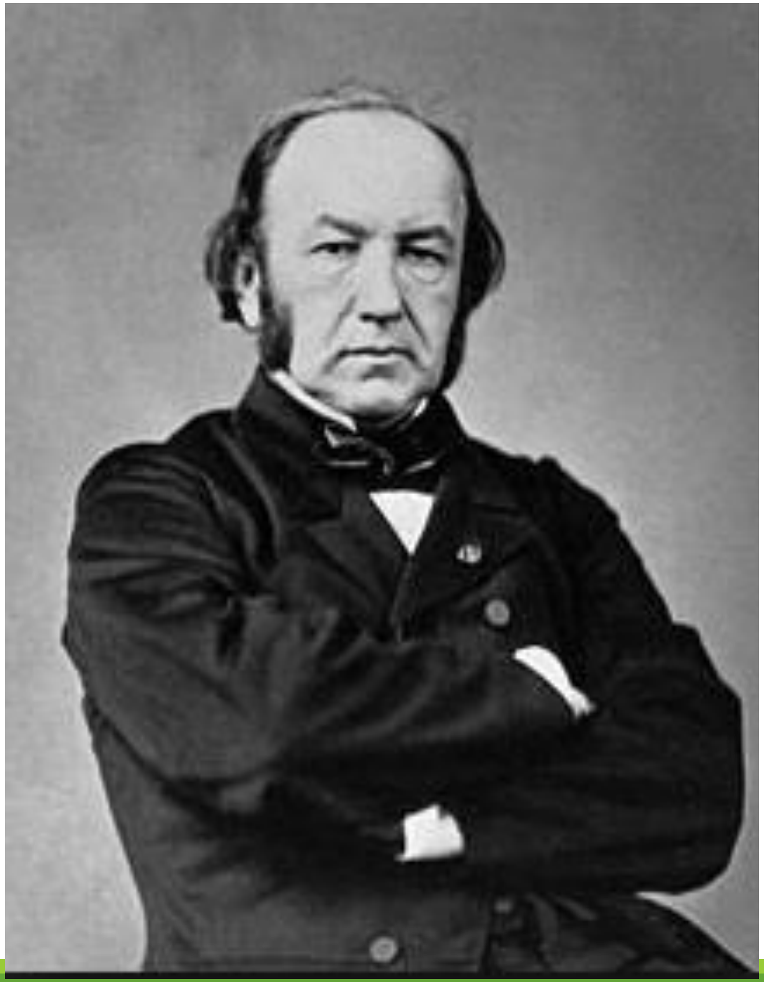
Pressure Measurement

Cardiac Output measurement

History

- Reverend Stephen hales-measured BP for the first time.
- First cardiac catheterization-Claude Bernard.
- First documented cardiac catherterization in living person-Werner Frossman.
- Nobel prize in med in 1956 along with Andre Counard and Dickinson richards

History



Basic Definitions

- Pressure wave: Complex periodic fluctuation in force per unit area-dynes/cm^2, mmhg.1 mm hg=1Torr=1/760 atm pressure
- Fundamental frequency: Number of times the pressure wave cycles in 1 second.
- Harmonic: Multiple of fundamental frequency.
- Fourier analysis: Resolution of any complex periodic wave into a series of simple sine waves of differing amplitude and frequency

What is a Pressure wave?

- Complex periodic fluctuation in force per unit area.
- One cycle-time interval between onset of one systole to subsequent systole.
- A pressure wave is the cyclical force generated by cardiac muscle contraction.
- Its amplitude and duration are influenced by various mechanical and physiological parameters
  - 1 .Force of the contracting chamber
  - 2.Surrounding structures - contiguous chambers of the heart pericardium, lungs, vasculature
  - 3.Physiological variables - heart rate, respiratory cycle

Fourier Analysis

- Each pressure wave is a summation of a series of simple sine waves of differing amplitude and frequency

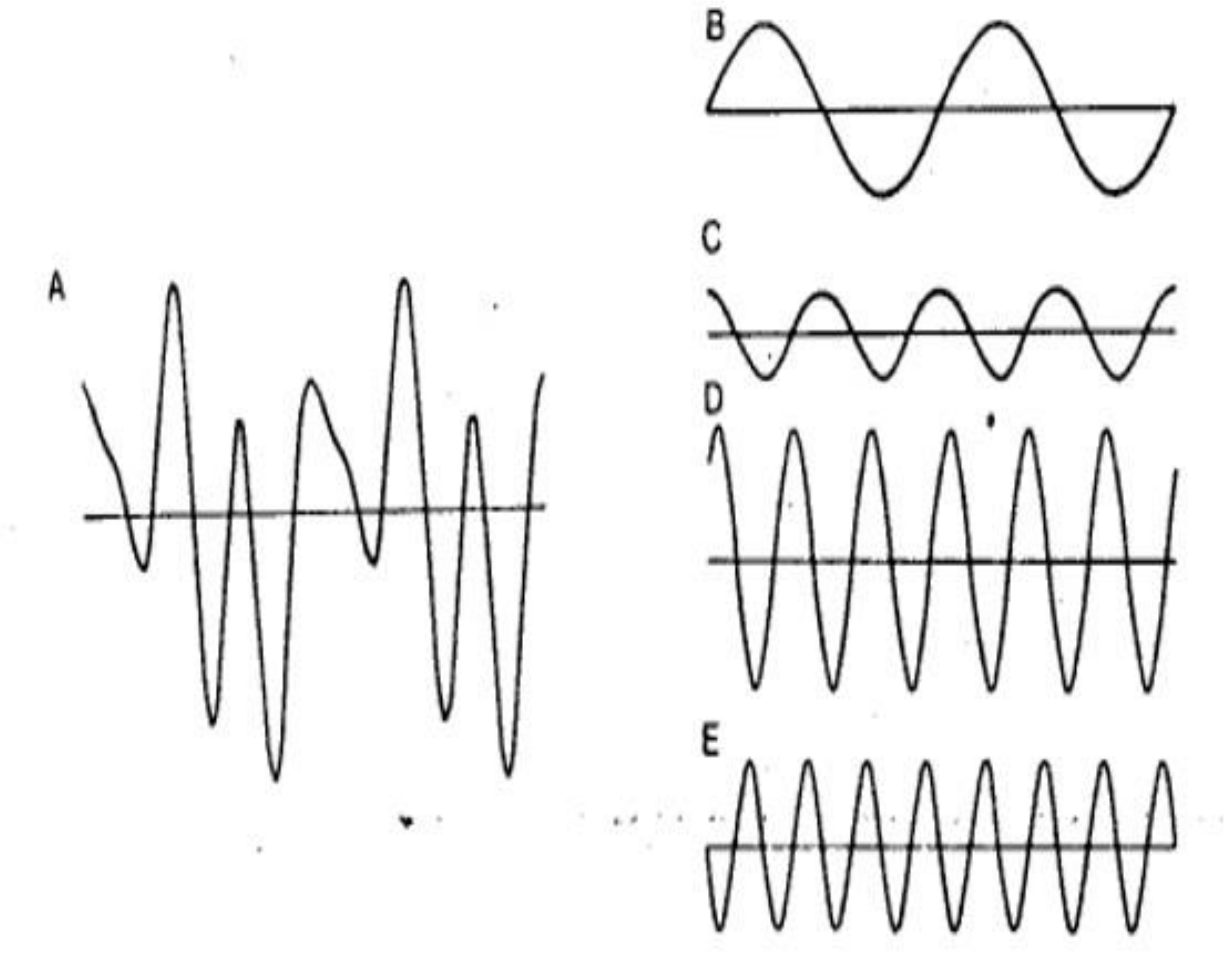
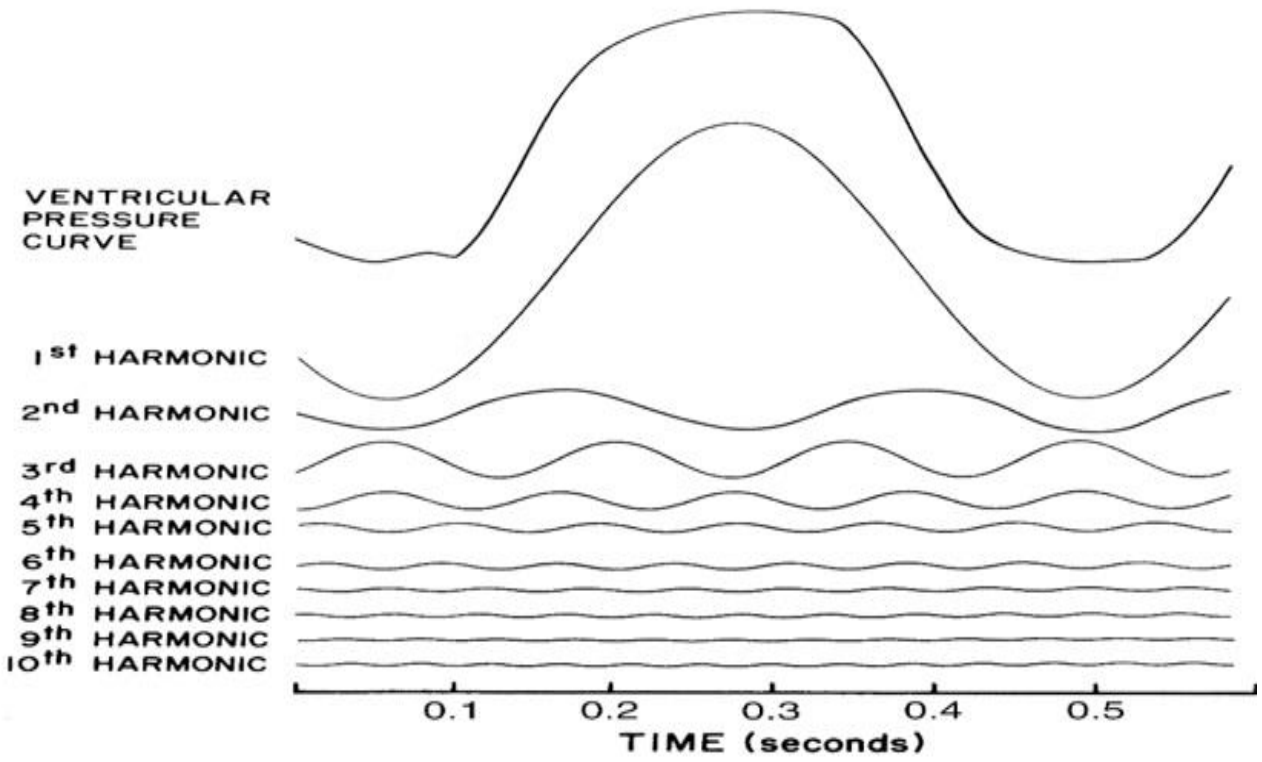


Fig. 1. The wave form A, a complex tone, is in fact the sum of the simple tones B-E. This is an illustration of Fourier's theorem that every vibration of frequency *f* can be analyzed mathematically into a series of sinusoidal vibrations with frequencies *f*, 2*f*, 3*f*, etc. These sinusoidal vibrations are called the harmonics

Wigger's principle



- Essential physiologic information is contained within 1st 10 harmonics of pressure wave fourier series.
- HR-120/min
- Fundamental frequency-2 Hz
- 10 th Harmonic-20 Hz.

Pressure measuring devices

Hurthle in 1898

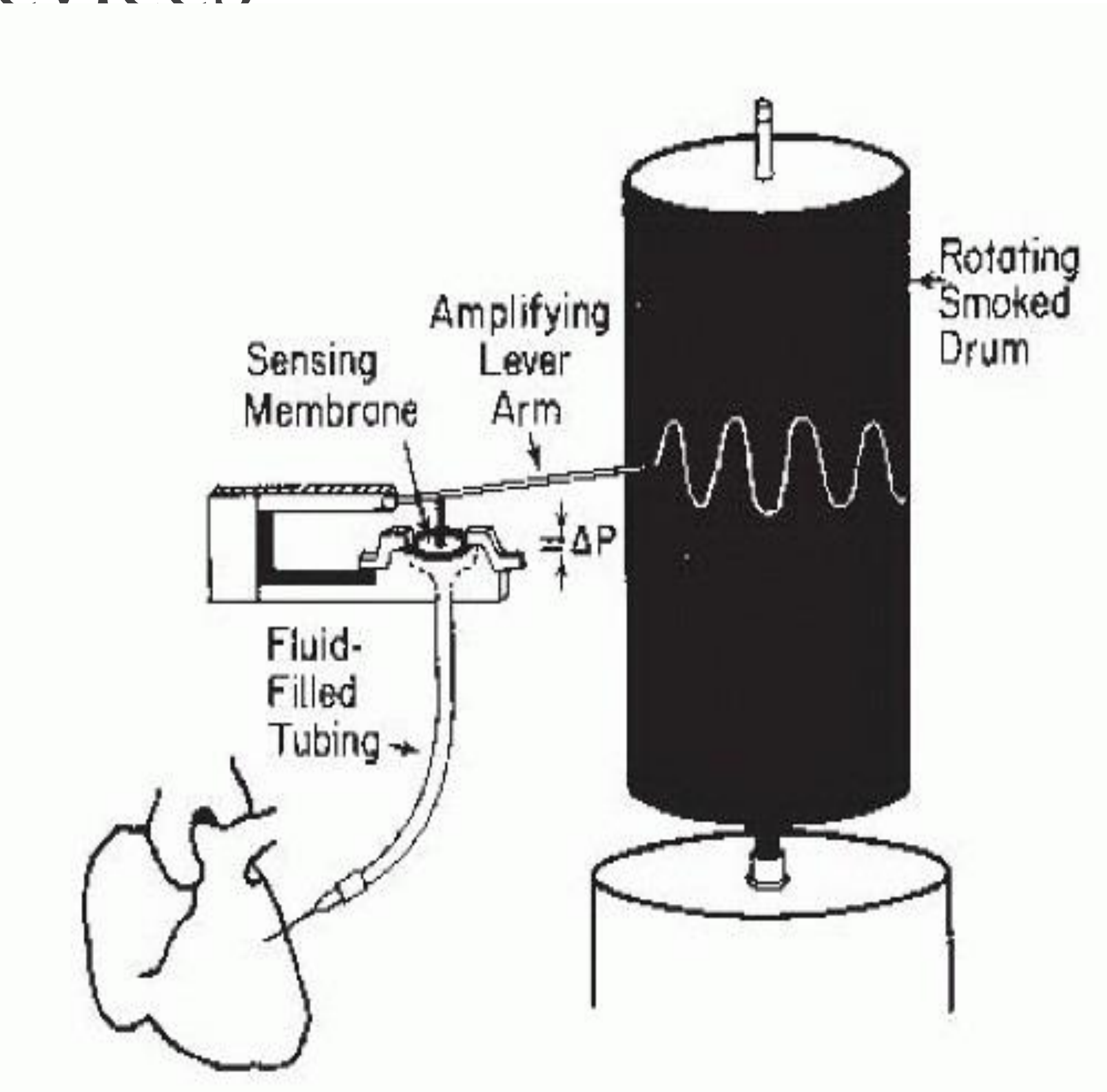
Modified by starling and wiggers.

Rotating smoked drum.

Amplifying arm lever.

Sensing membrane.

Fluid filled tubing



Sensitivity

- Ability to detect small changes in pressure signals.
- More rigid the sensing membrane, lower is the sensitivity.

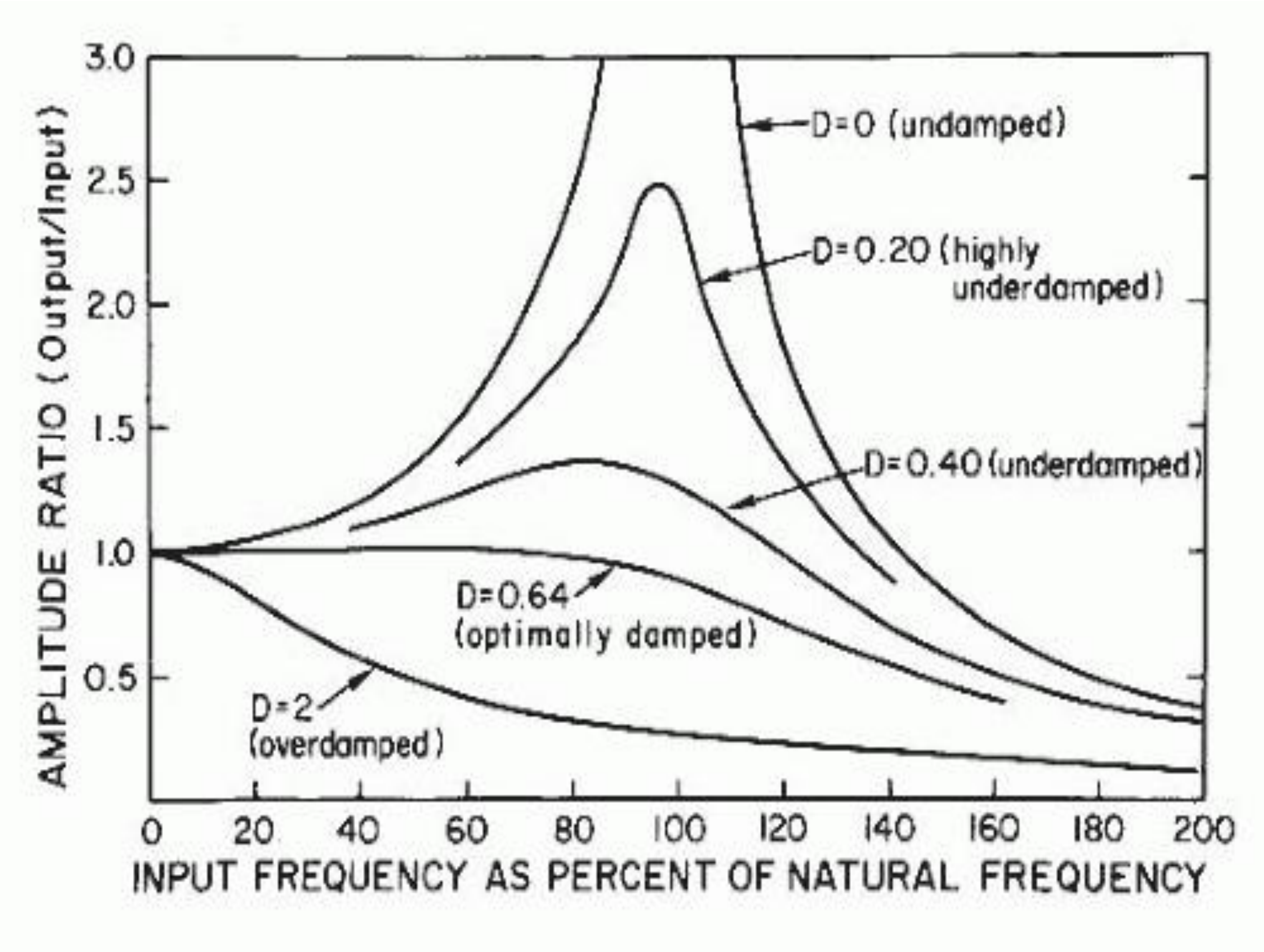
Frequency response

- Ratio of output amplitude to input amplitude over wide range of frequencies.
- Range of good frequency response is improved by stiffening the membrane.

Natural frequency

- Frequency at which fluid oscillates in a catheter when it is shock excited.
- Frequency of an input pressure wave at which the ratio of output/input amplitude of an undamped system is maximal

Natural frequency and damping



- Amplitude of output signal augmented when frequency of input signal approaches natural frequency.
- D=damping coefficient.
- Useful frequency response range of commonly used pressure measurement is less than 20 Hz.

Damping

- Means of dissipating energy.
- Optimal damping dissipates energy slowly.
- Amplitude and frequency of oscillations are reduced.
- Natural frequency of system is reduced.
- Increased viscosity of the medium, prevents overshoot andweight returns to original position.
- Prevents overshoot artefacts but diminished frequency response

Damping proportional to viscosity of fluid

Catheter radius

Greater fluid viscosity
Smaller catheter radius

Greater Damping

What frequency response is desirable ?

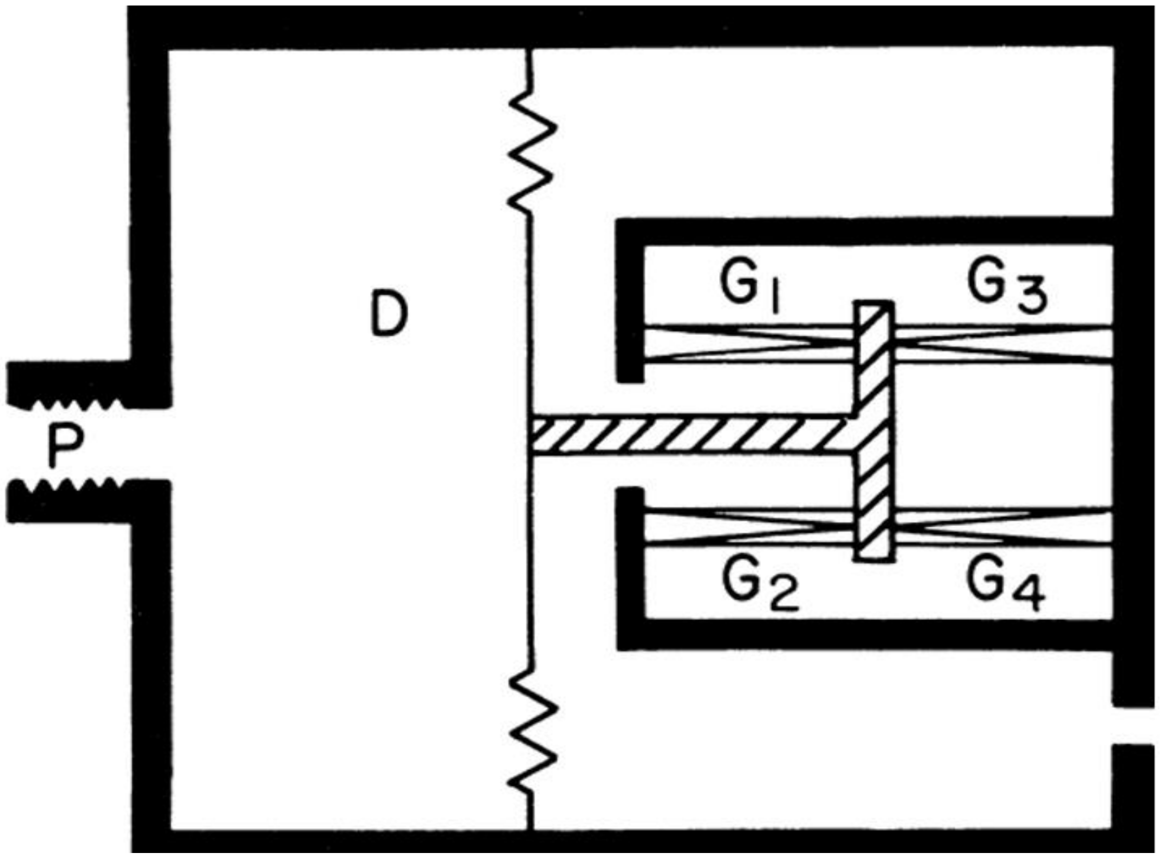
- To ensure high frequency response range- highest natural frequency and optimal damping.

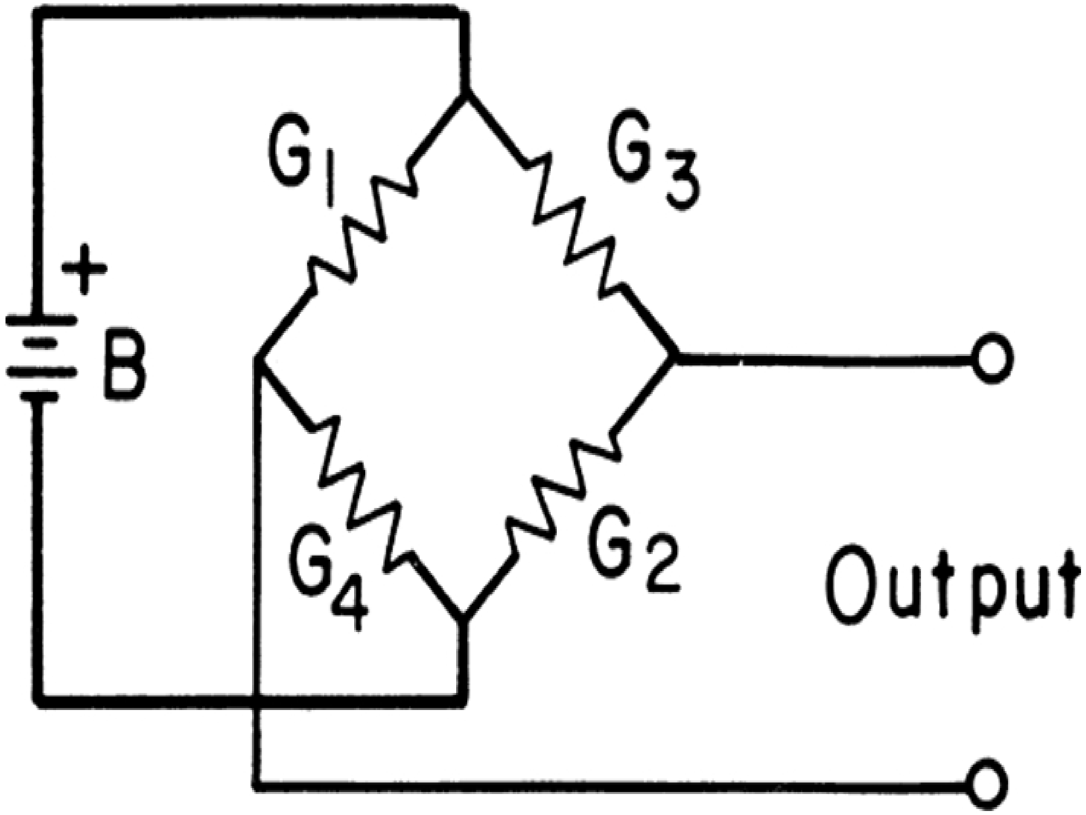
$$\text{Natural frequency-} \qquad \frac{\text{Catheter radius}}{\text{Catheter length}} \text{ x } \frac{1}{\sqrt{\text{fluid}}\ \text{density x catheter compliance}}$$

$$\left.\begin{array}{l}\text{Shorter catheter}\\ \text{Larger catheter lumen}\\ \text{Lighter fluid}\end{array}\right\} \qquad \text{Higher natural Frequency}$$

- Highest natural frequency- Short, wide bore, stiff catheter connected to its transducer without intervening tubings, low density fluid without air bubble-over damped.

Transforming pressure wave to electrical signals

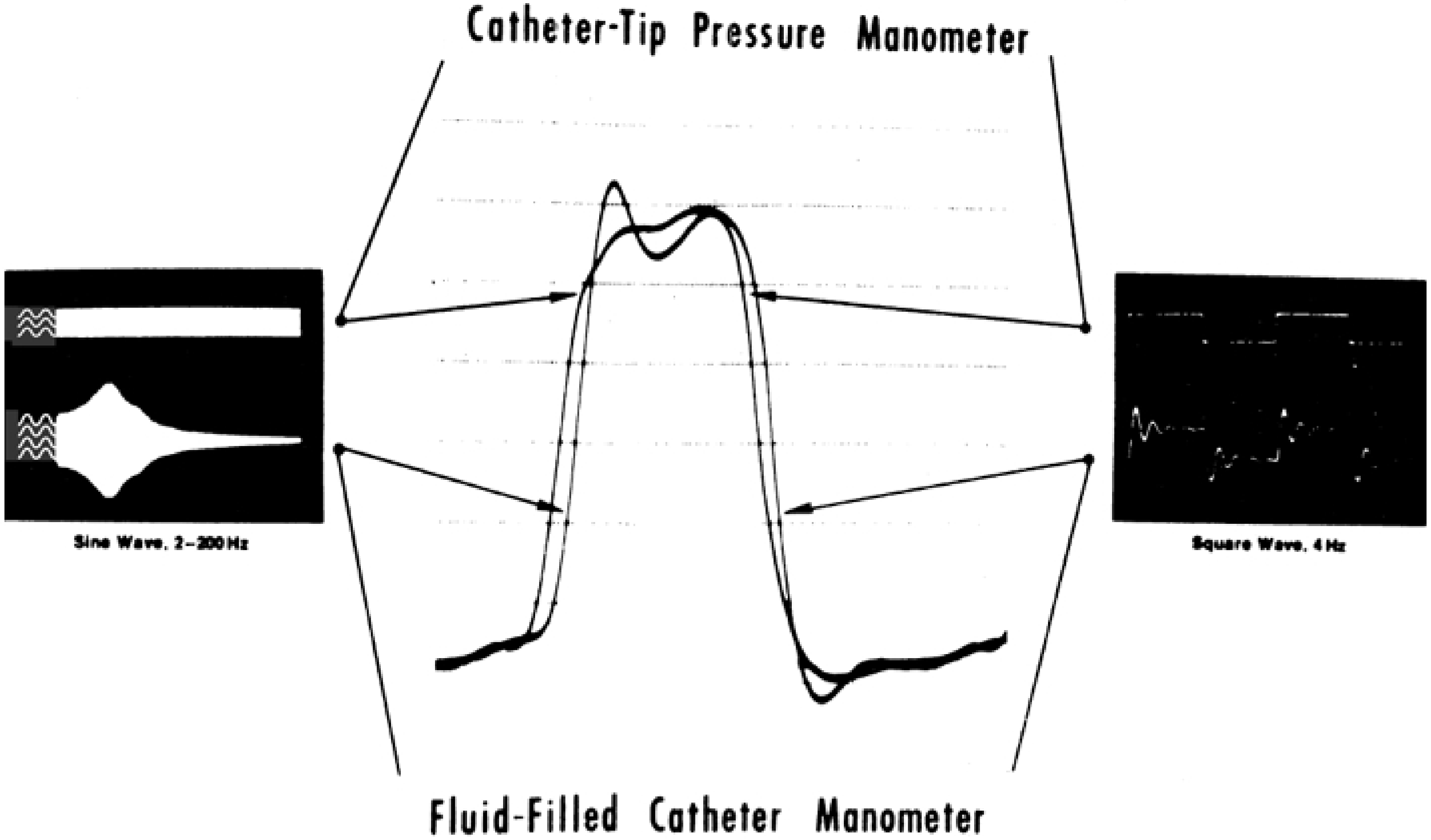




Pressure measurement Systems

Micro manometer

Fluid filled systems



Pressure measurement system

Use electrical guage.

Uses principle of wheat stone bridge.

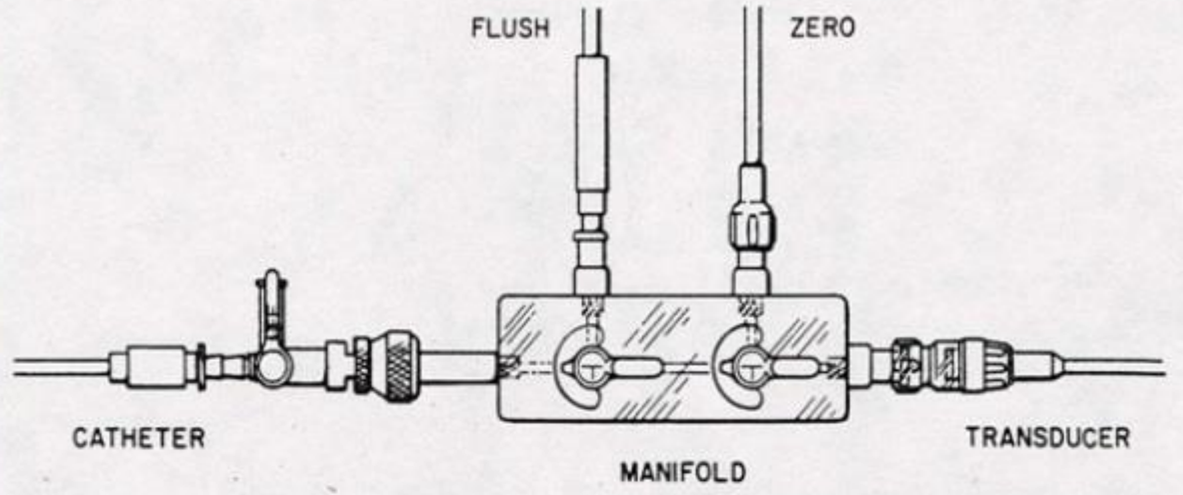
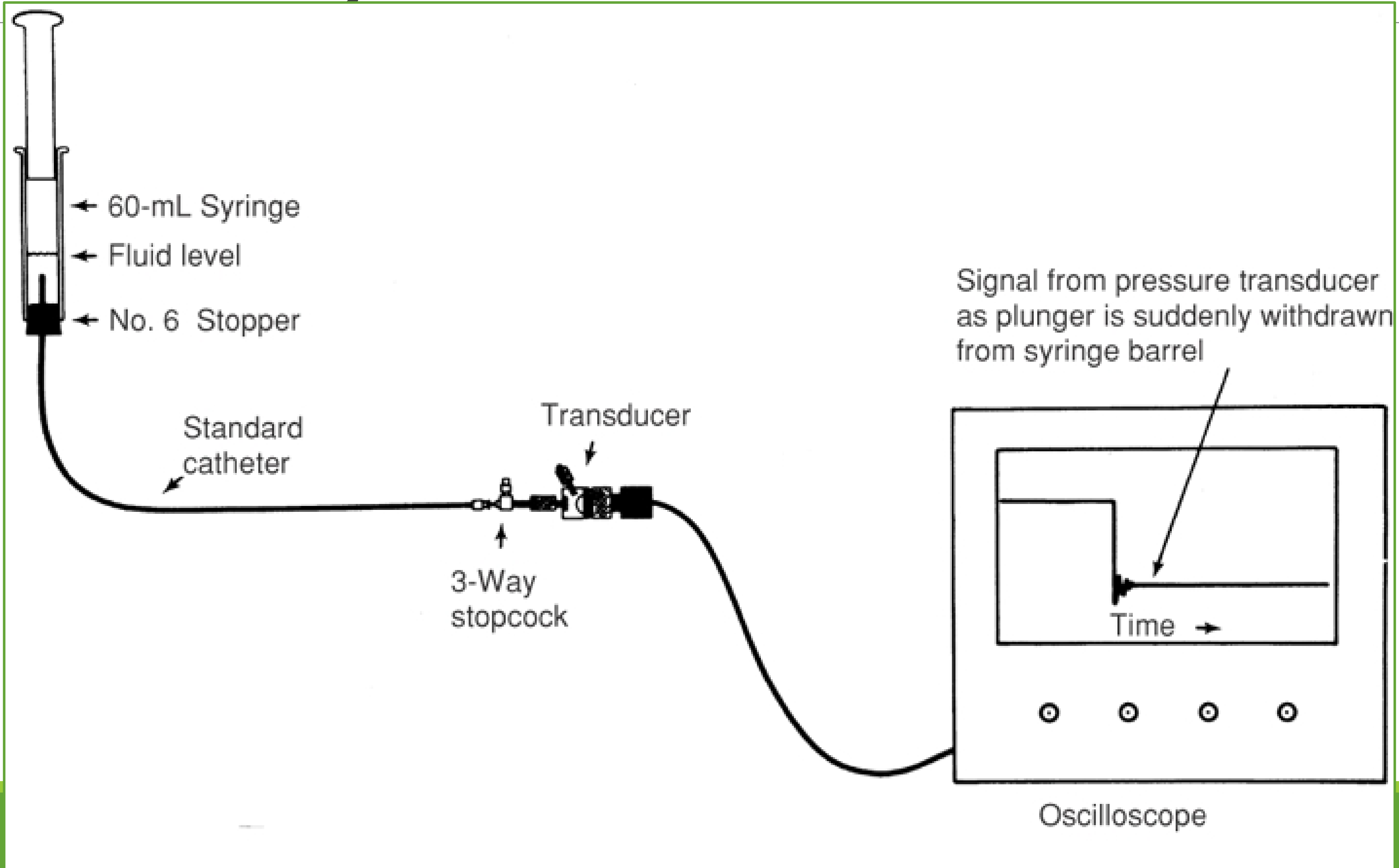


FIG. 7.9. A practical system for pressure measurement with excellent frequency response. The catheter is connected by a stopcock to a manifold, which is connected at its other end to a small-volume fluid-filled pressure transducer. The manifold's two sidearms are connected by fluid-filled tubing to a zero pressure reference level and to a pressurized flush solution.

Evaluation of dynamic response characteristics of the catheter-transducer system



Zero Level

Should be positioned 5 cm below the left sternal border.

Each case should measure AP diameter at the level of angle of lewis

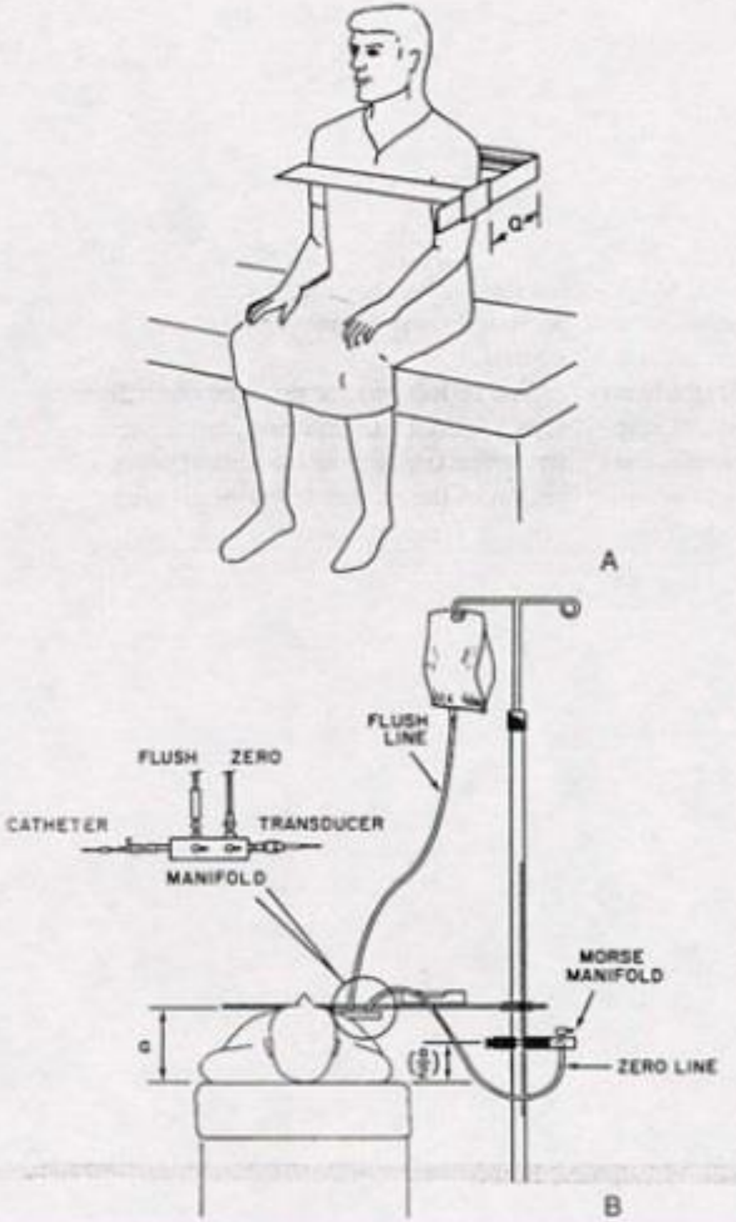
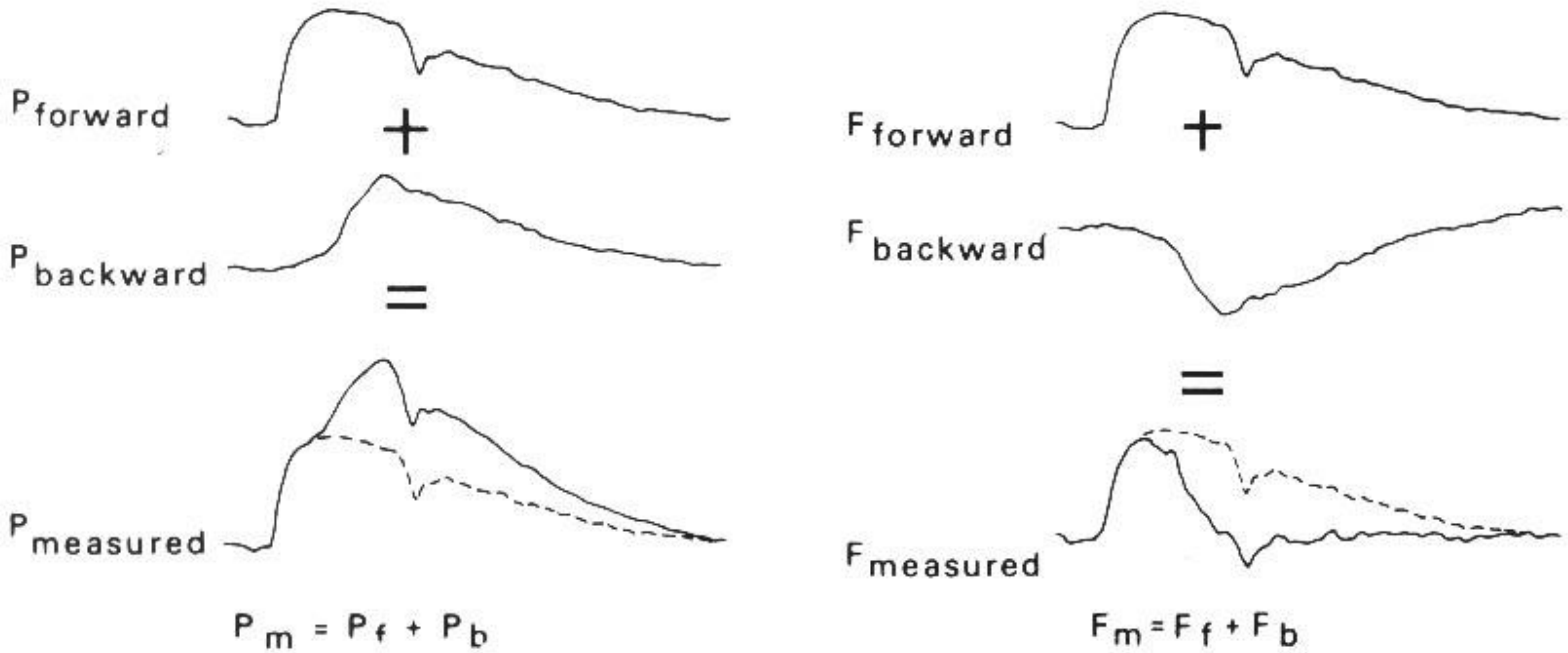


FIG. 7.10. A: Technique for measurement of a patient's anteroposterior diameter (a), using a metal chest caliper. **B:** Establishment of zero level. (See text for detailed explanation.)

Physiologic Characteristics



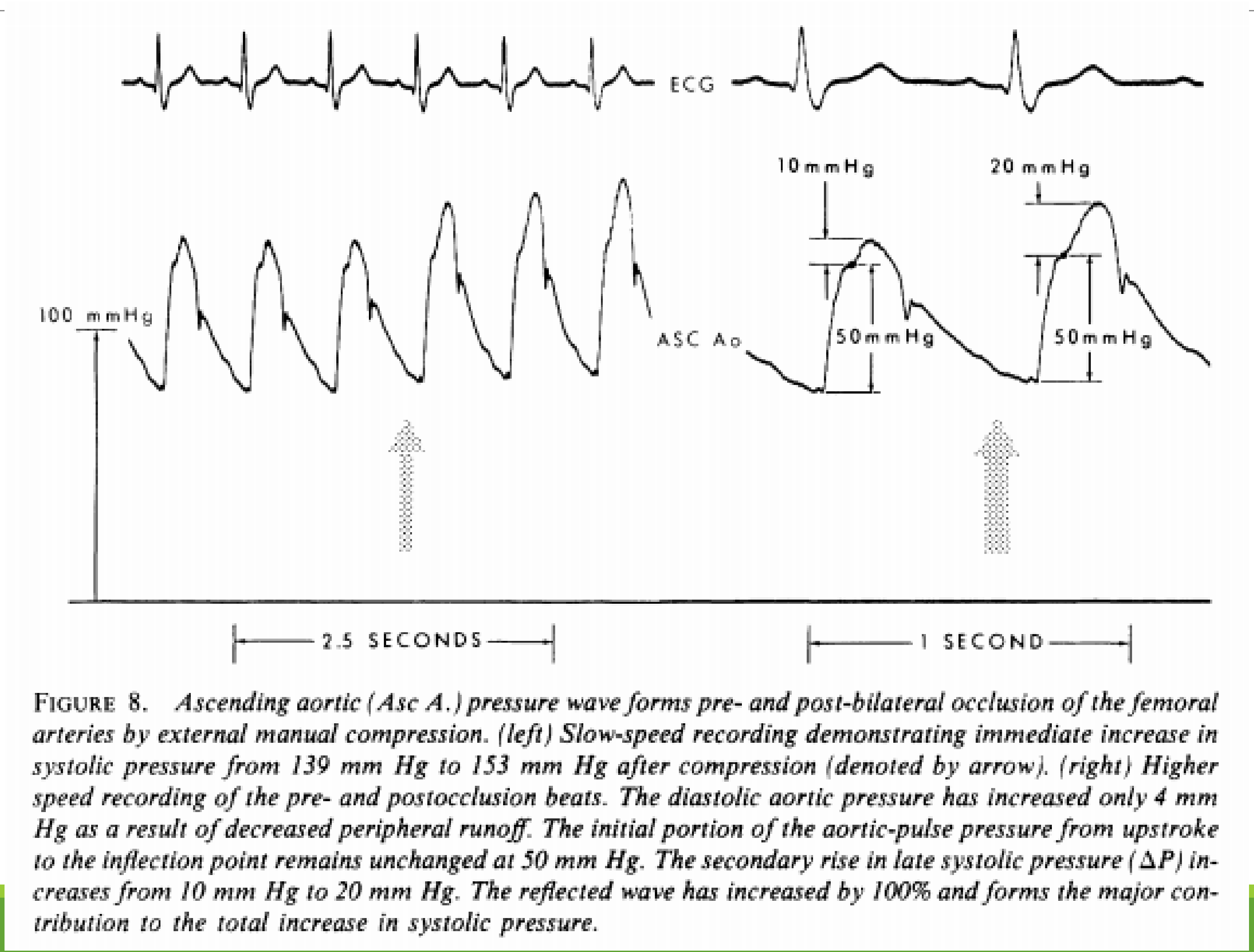
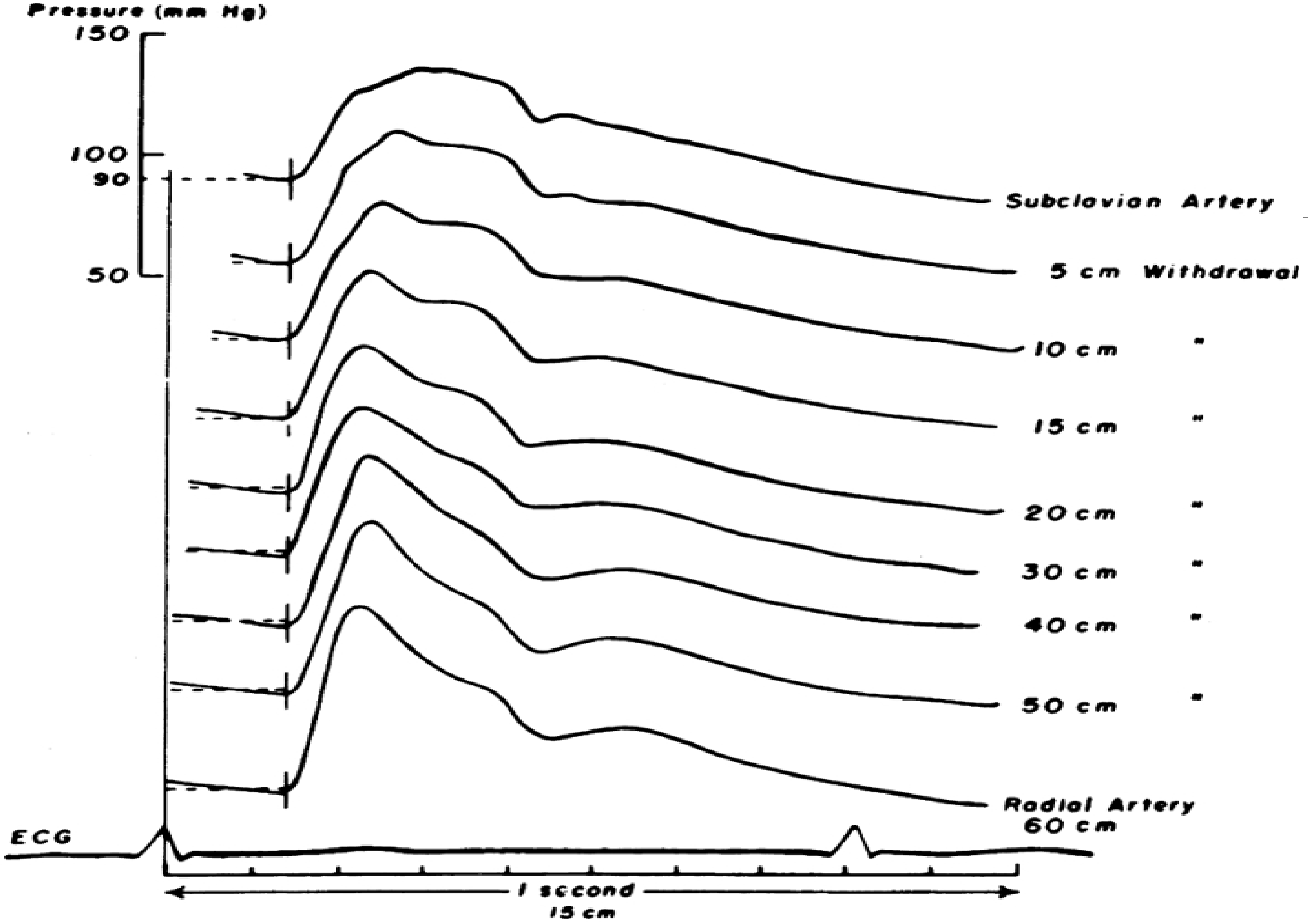


FIGURE 8. *Ascending aortic (Asc A.) pressure wave forms pre- and post-bilateral occlusion of the femoral arteries by external manual compression. (left) Slow-speed recording demonstrating immediate increase in systolic pressure from 139 mm Hg to 153 mm Hg after compression (denoted by arrow). (right) Higher speed recording of the pre- and postocclusion beats. The diastolic aortic pressure has increased only 4 mm Hg as a result of decreased peripheral runoff. The initial portion of the aortic-pulse pressure from upstroke to the inflection point remains unchanged at 50 mm Hg. The secondary rise in late systolic pressure (ΔP) increases from 10 mm Hg to 20 mm Hg. The reflected wave has increased by 100% and forms the major contribution to the total increase in systolic pressure.*


Pressure (mm Hg)
150
100
90
50
Subclavian Artery
5 cm Withdrawal
10 cm "
15 cm "
20 cm "
30 cm "
40 cm "
50 cm "
Radial Artery
60 cm
ECG
1 second
15 cm

Factors that influence magnitude of reflected waves

Augmented pressure wave reflections

- Vasoconstriction
- Heart failure
- Hypertension
- Aortic / iliofemoral obstruction
- Post-valsalva release

Diminished pressure wave reflections

- Vasodilation (physiologic / pharmacologic)
- Hypovolemia
- Hypotension
- Valsalva maneuver strain phase

Wedge Pressure

Pressure obtained when an end-hole catheter is positioned in a “designated” blood vessel with its open end-hole facing a capillary bed.

- No connecting vessels conducting flow into or away from the “designated” blood vessel between the catheter’s tip and the capillary bed

Can be *measured only in the absence of flow*, allowing pressure to equilibrate across the capillary bed

Errors and Artifacts

- Deterioration of frequency response.
- Introduction of air permits damping and reduces natural frequency by serving as added compliance.
- Flushing-restores the frequency response of system.
- Types- Movement artifacts.
- End Pressure Artifacts.
- Catheter tip artifacts.

Movement Artifact(whip Artifact)

- Produced due to motion of tip of the catheter within the measured chamber that increase the oscillations.
- May produce superimposed waves of ±10 mm Hg.
- Particularly common in PA.
  - Render systolic and to a lesser extent diastolic pressures unreliable.
  - No way to fix it internally.
  - Stabilize externally.
  - If whip noted -consider using mean pressures. (usually not affected)

End pressure artifact

- An end-hole catheter measures an artificially elevated pressure because of streaming or high velocity of the pressure wave.
- Flowing blood- sudden halt- K E is converted to pressure.
- This added pressure may range from 2-10 mm Hg.

Catheter impact artifact

- When the catheter is struck by the walls or valves of the cardiac chambers.
- Common with the pigtail catheter in the LV, where the MV hits the catheter as they open in early diastole

Systolic Pressure amplification in periphery

- Peak SBP in radial, brachial, femoral > peak SBP in central Aorta by 20 mmhg.
- Mean arterial Pressure remains same.
- Largely as a consequence of reflected wave from Aortic bifurcation, arterial branching, small peripheral vessels
- Reinforce the peak and trough of the anterograde Pressure wave.
- Masks pressure gradients in LV or across aortic valve

Micromanometer –Tipped Catheters

- Fluid filled system shows distortion of wave forms.
- For precise, undistorted ,high fidelity pressure recordings.
- Micro mamometer chips at the end of catheters.
- Interposing fluid column is eliminated.
- Have higher natural frequencies and more optimal damping characteristics.
- To assess pressure waveform contours in a tachycardia situation, rate of ventricular pressure rise(dp/dt) etc.
- Limitation- additional cost, fragility , time needed for properly calibrating and using the system

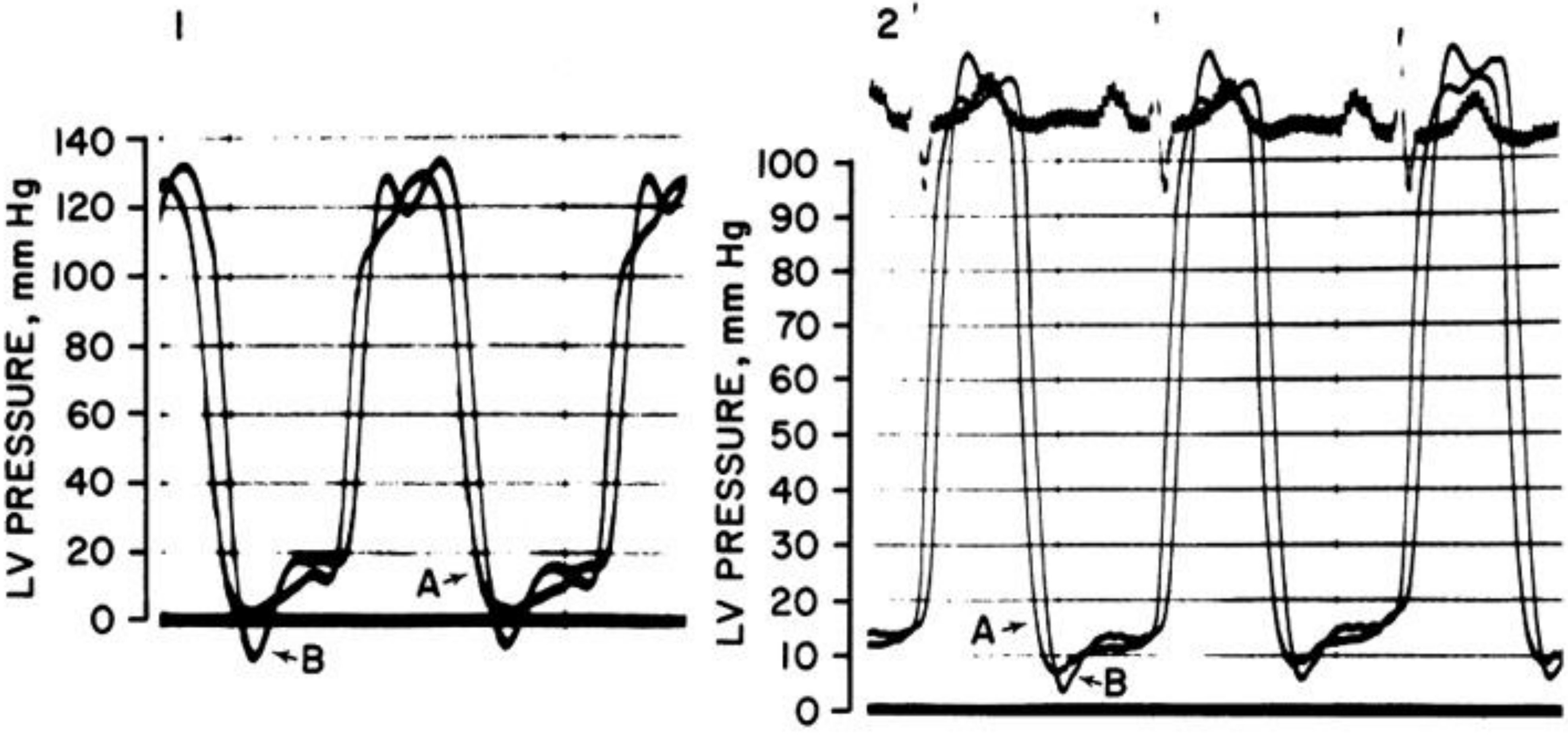
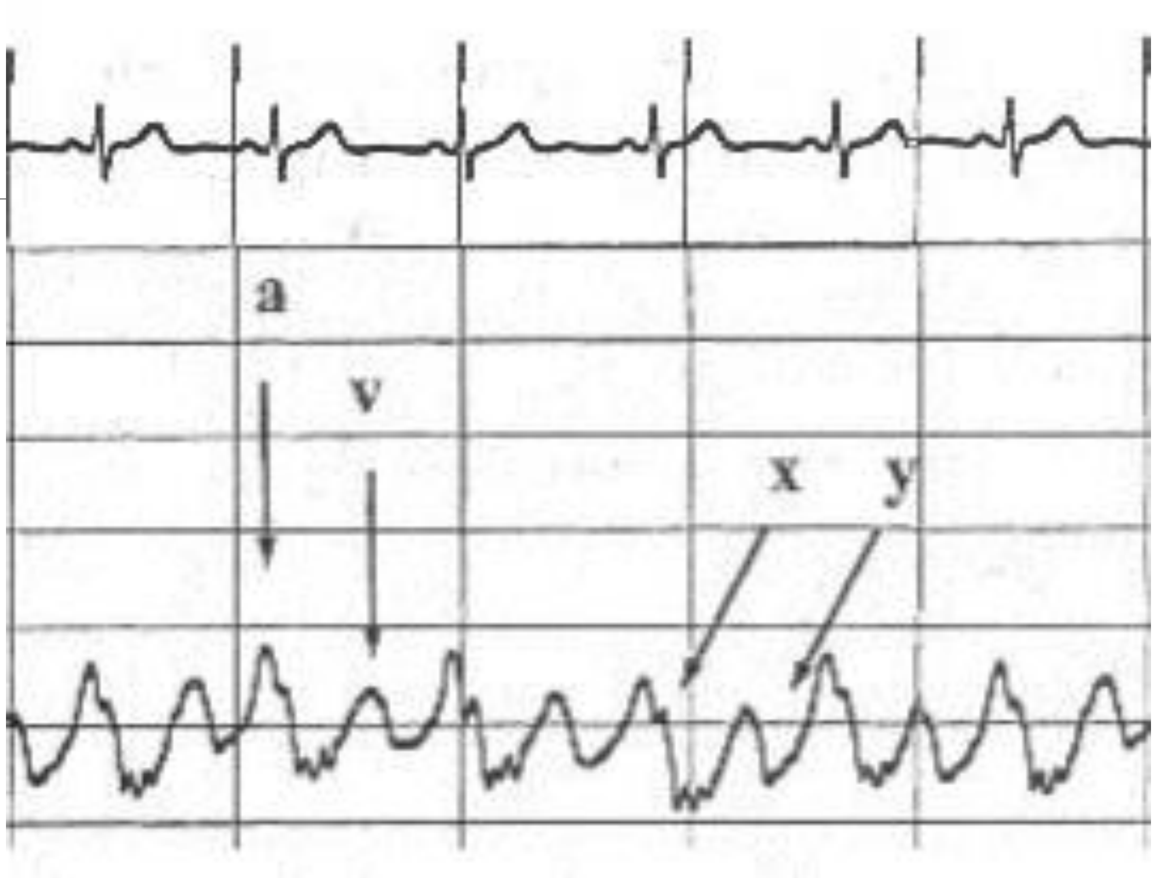


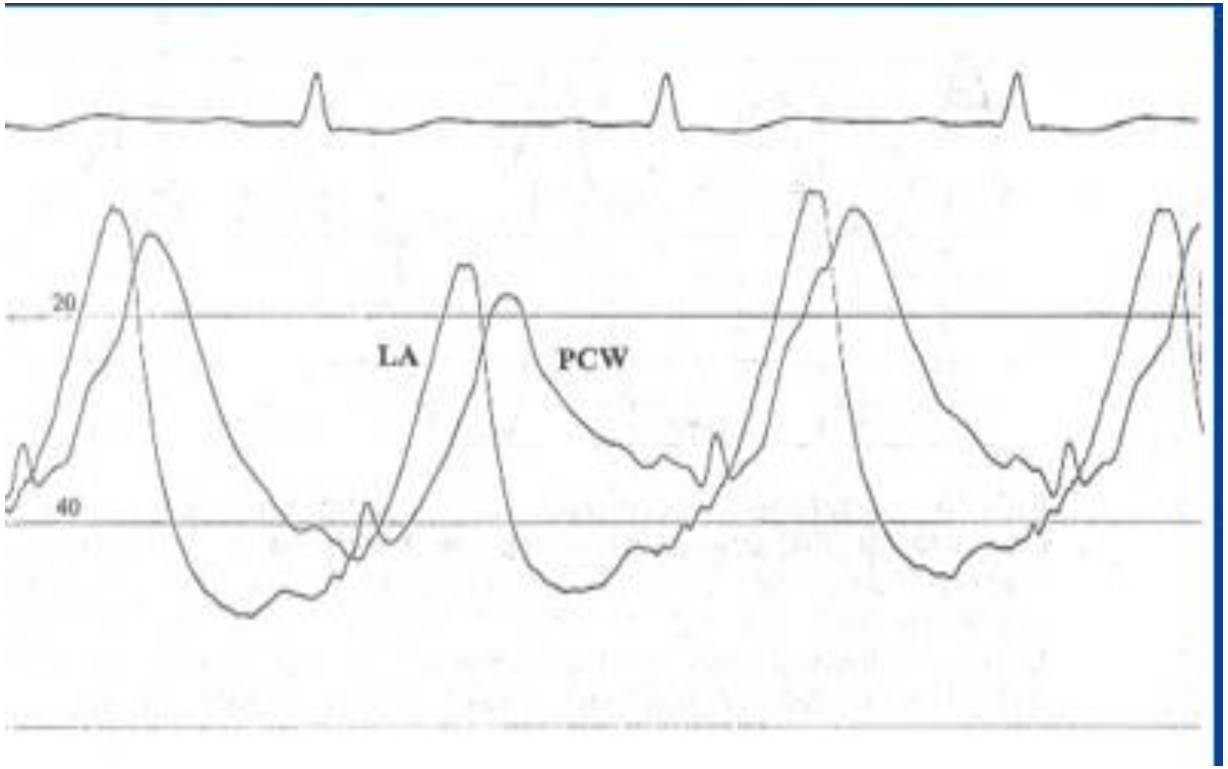
Figure 7.16 Left ventricular (LV) pressure signals as recorded with a micromanometer and with a system using long, fluid-filled tubing and several interposed stopcocks between the pressure transducer and the 7F NIH catheter. The micromanometer tracing is labeled A, and the fluid-filled catheter tracing is labeled B. Note both the early diastolic and the early ejection phase overshoots recorded with the fluid-filled catheter, indicating a poor frequency response, especially in the graph on the left.

Right Heart Catheterization-Right Atrial Pressure

- “a” wave
  - Atrial systole
- “c” wave
  - Protrusion of TV into RA
- “x” descent
  - Relaxation of RA
  - Downward pulling of tricuspid annulus by RV contraction
- “v” wave
  - RV contraction
  - Height related to atrial compliance & amount of blood
  - Smaller than a wave
- “y” descent
  - TV opening and RA emptying into RV

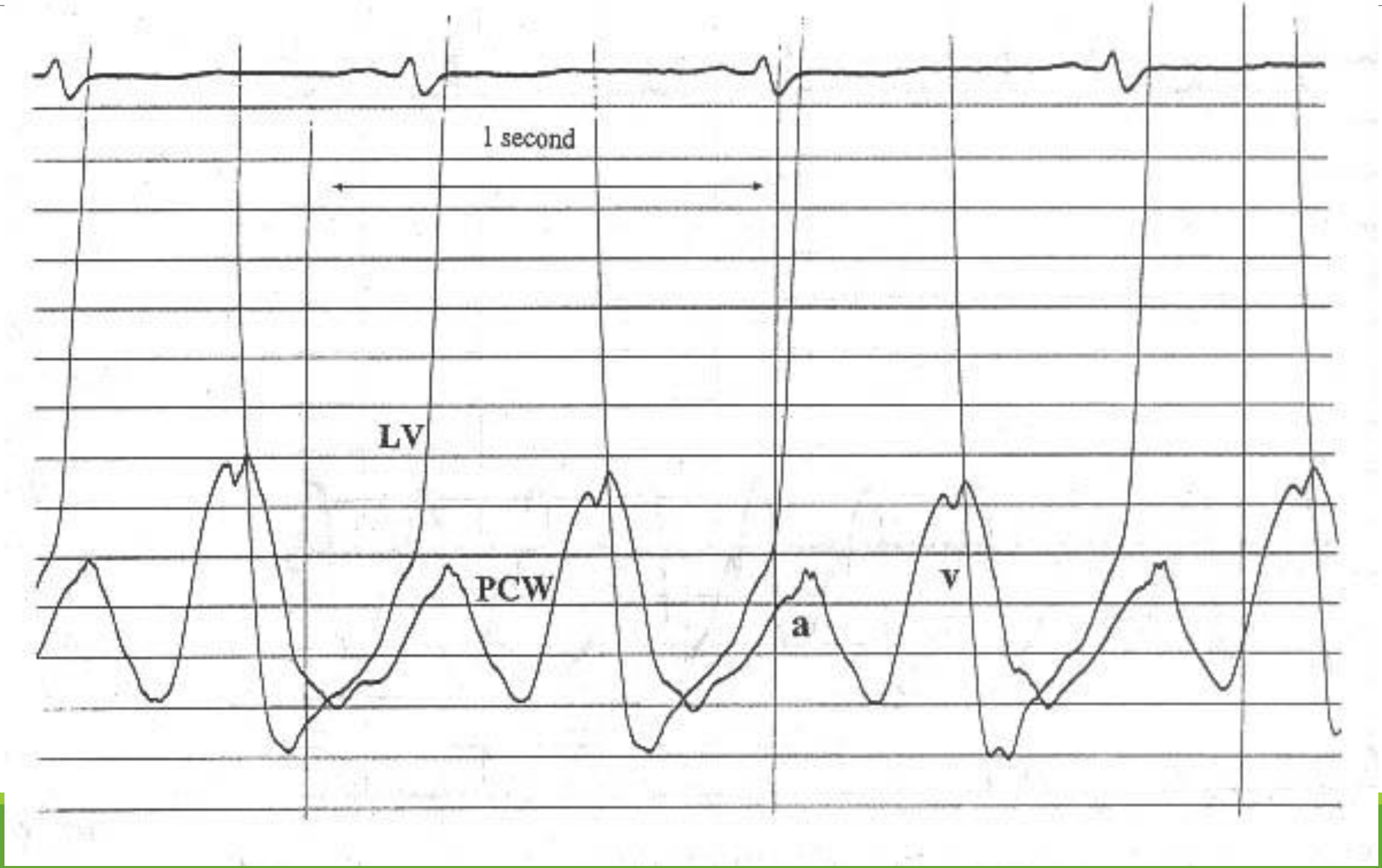


Right Heart Catheterization-Left Atrial and PCW P

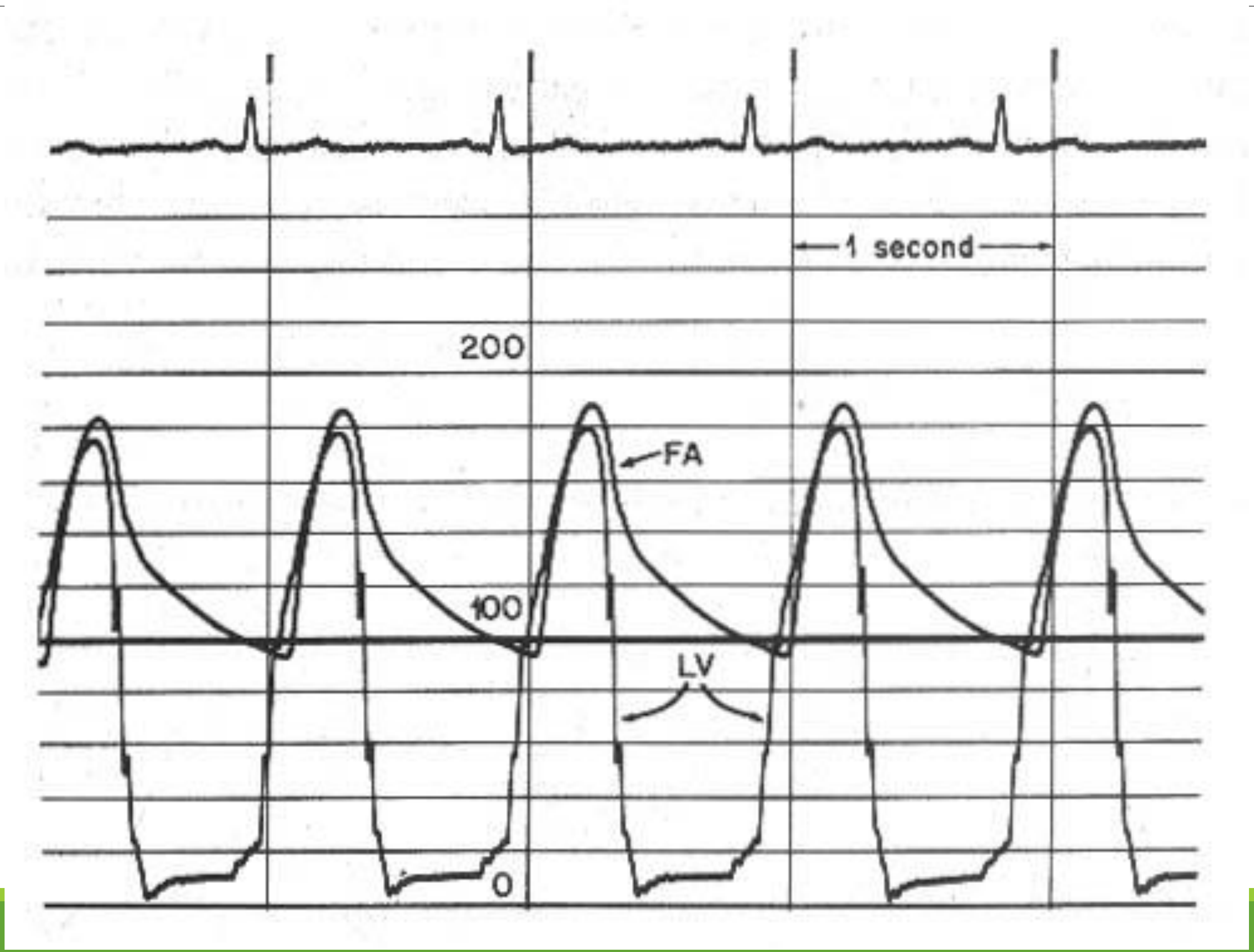


PCW tracing “approximates” actual LA tracing but is slightly delayed since pressure wave is transmitted retrograde through pulmonary veins

Left Heart Catheterization-Left Ventricular Diastole



Left Heart Catheterization-Left Ventricular Systole



CARDIAC OUTPUT MEASUREMENT

Introduction

Quantity of blood delivered to the systemic circulation per unit time expressed in L/min

Techniques of measurement:

- Fick-Oxygen Method
- Indicator-Dilution Methods
- Indocyanine Green
- Thermodilution

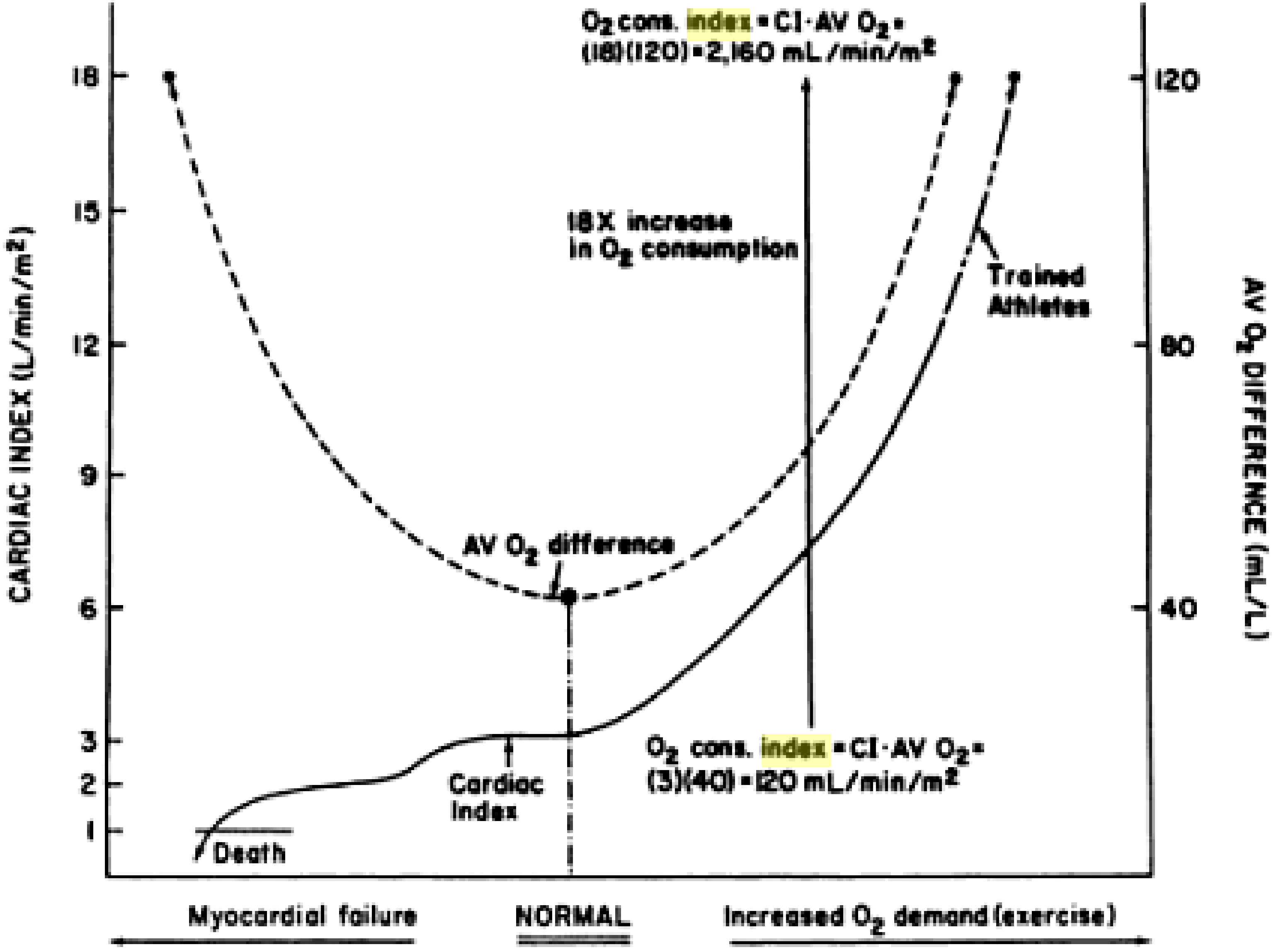
Extraction reserve and CO

- The extraction of a particular nutrient expressed as A-V difference across that tissue.
- The factor by which the arterio venous difference can increase at constant cardiac output, owing to changes in metabolic demand, termed as extraction reserve.
- Normal extraction reserve for O_2- 3.
- Under extreme metabolic demand, tissues can extract upto 120ml of O_2(40×3) from each liter of blood delivered.

- As the cardiac output falls, extraction of O_2 by the tissues increases.
- Upto 1/3 fall in C.O can be compensated by 3 times increase in extraction reserve.

- C.O below one third of normal- incompatible with life (CI $\leq$ 1.0 L/min/m^2).
- Upper limit of C.O in trained athletes- 600% of resting output.

- Under extreme exercise, total body O_2 requirement increases to 18 times, which is met by 6 fold rise in C.O and 3 fold rise in extraction reserve


O_2 cons. index = CI · AV O_2 =
(18)(120) = 2,160 mL/min/m^2
18X increase in O_2 consumption
Trained Athletes
AV O_2 difference
Cardiac Index
Death
O_2 cons. index = CI · AV O_2 =
(3)(40) = 120 mL/min/m^2
CARDIAC INDEX (L/min/m^2)
18
15
12
9
6
3
2
1
AV O_2 DIFFERENCE (mL/L)
120
80
40
Myocardial failure
NORMAL
Increased O_2 demand (exercise)

Fick’s Oxygen Method

Adolph fick-1870.

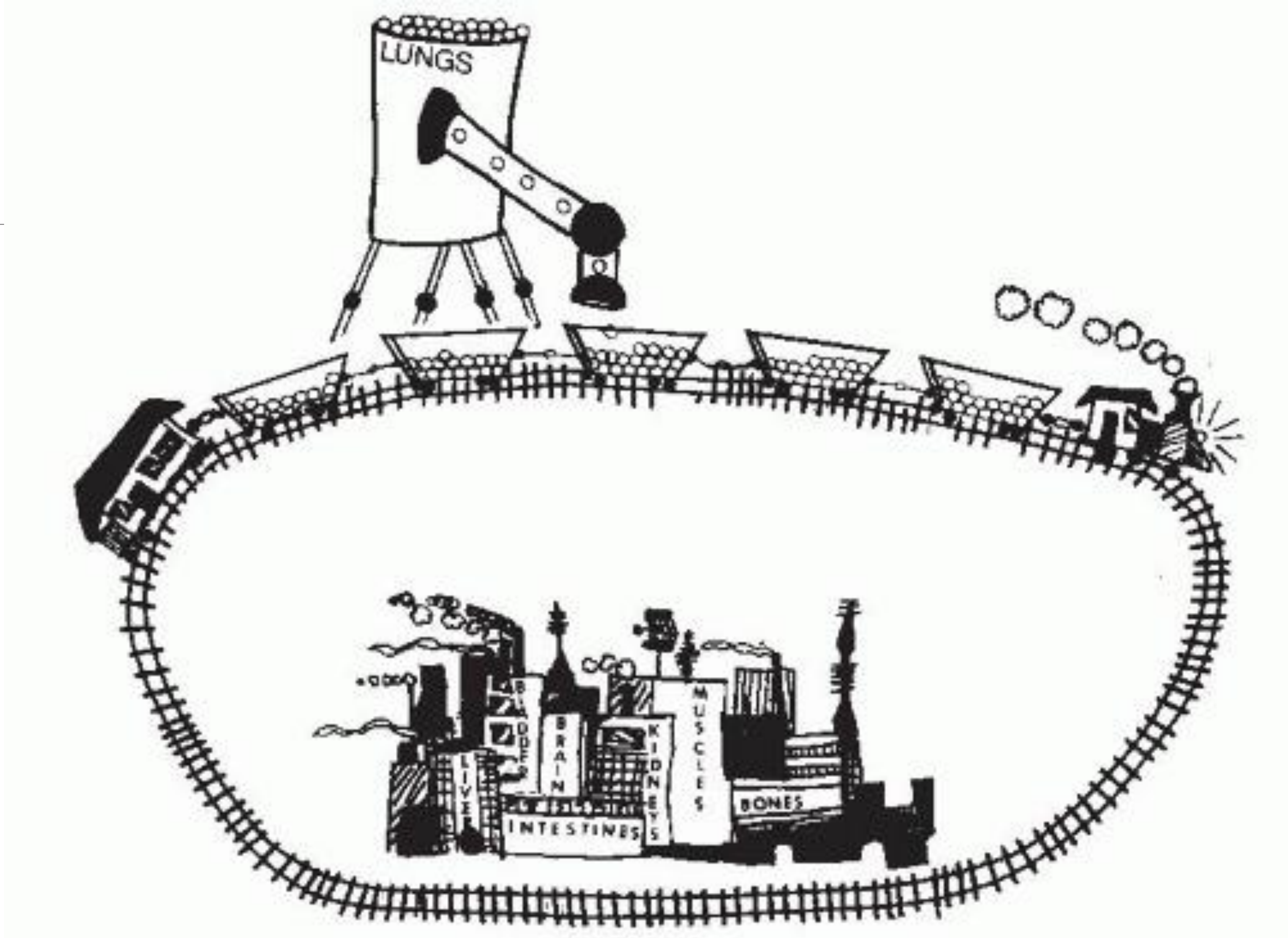
Principle

The total uptake or release of any substance by an organ is the product of blood flow to the organ and the arterio venous concentration difference of the substance.

If no intra cardiac shunt PBF=SBF

$$Q= \frac{\text{OXYGEN CONSUMPTION}}{\text{Arterio venous } O_2 \text{ Difference}}$$

In the absence of a shunt, systemic blood flow (Qs) is estimated by pulmonary blood flow (Qp).


LUNGS
LIVER
BLADDER
BRAIN
KIDNEYS
MUSCLES
BONES
INTESTINES

Oxygen consumption

- Uptake of oxygen from room air by the lungs is measured.

- Douglas bag method
- Polarographic method
- Paramagnetic method

DOUGLAS BAG METHOD

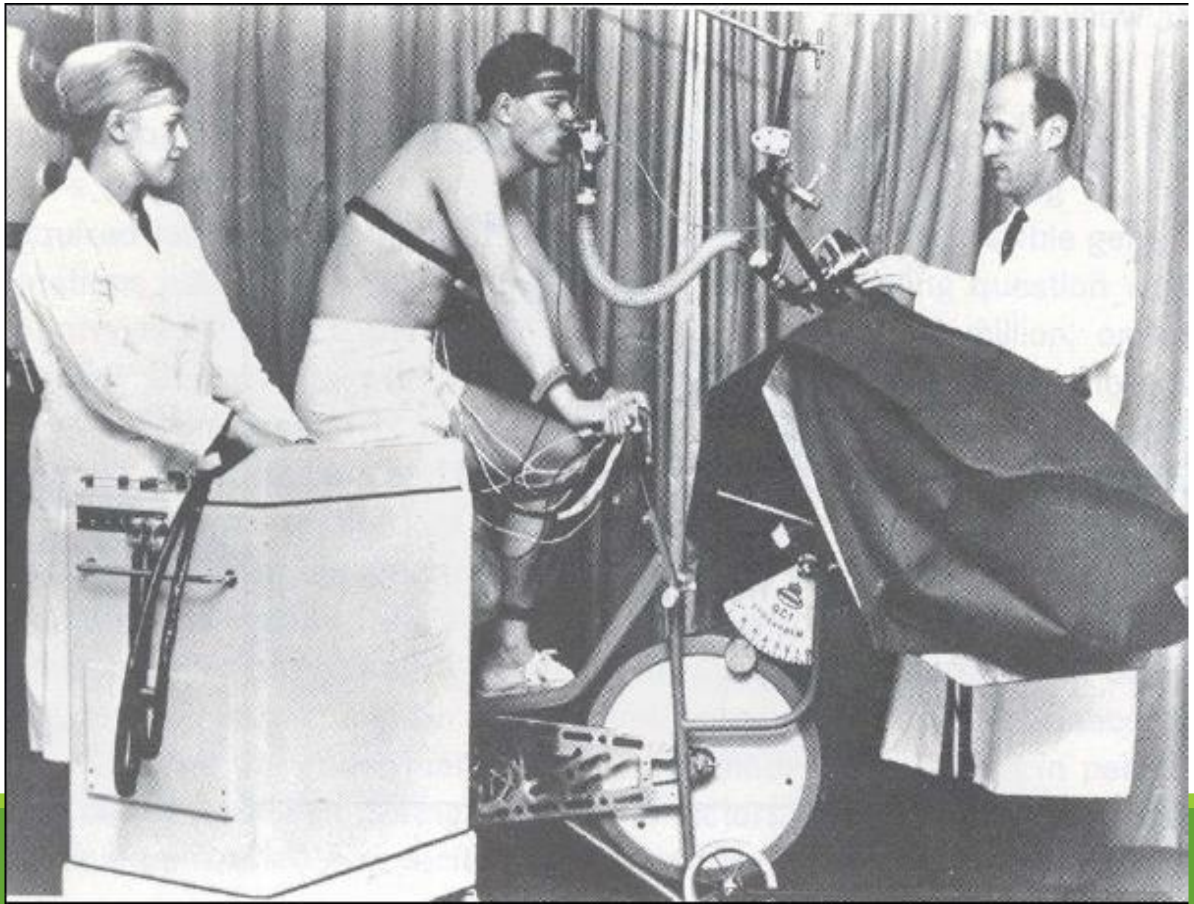
- Older
- A timed sample of patients expired air is collected in a Douglas bag & analyzed for O2 content and (Beckman oxygen analyzer) and volume
- O2 content of room air is also measured
- Oxygen consumption per l per minute is calculated

POLAROGRAPHIC METHOD

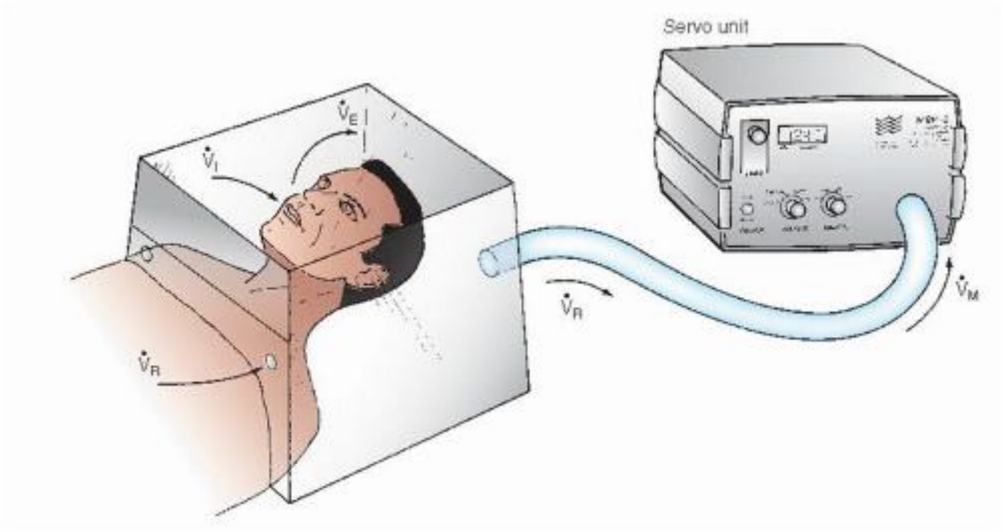
- Metabolic rate meter by Waters instruments
- Parts: oxygen hood /mask
- Polaro graphic oxygen sensor cell
- V o2=O2 content in the room air – O2 content in the air flowing past the polaro graphic cell
- Respiratory quotient is assumed

Methods of oxygen consumption

DOUGLAS BAG METHOD



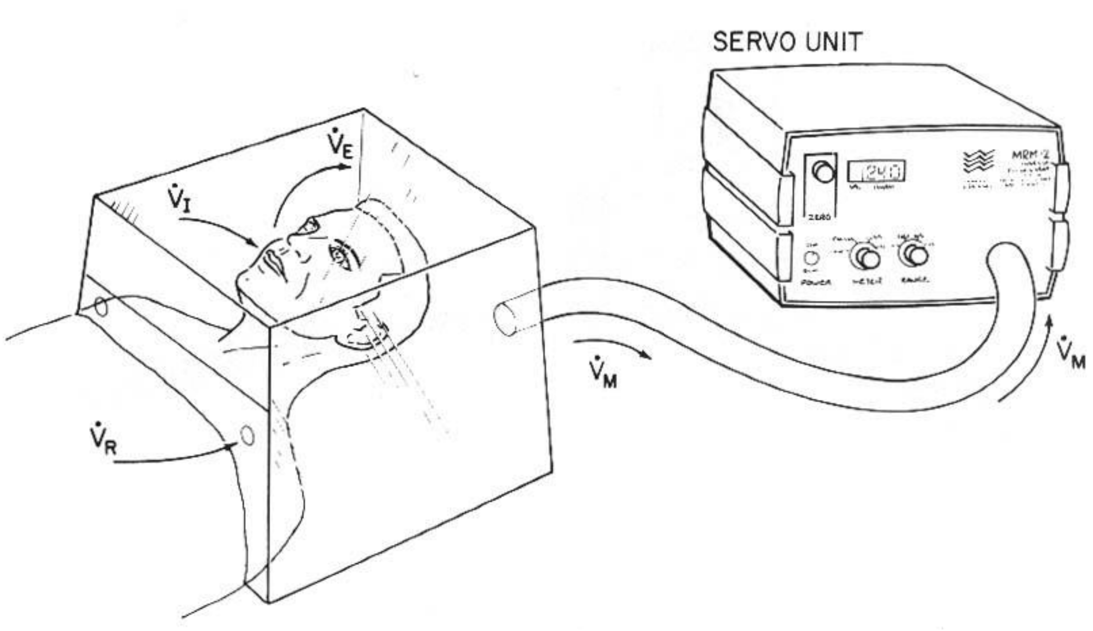
MRM –WATER'S INSTRUMENTS



Polarographic O_2 Method

- Metabolic rate meter
- Device contains a polaro graphic oxygen sensor cell, a hood and a blower of variable speed connected to the oxygen sensor.
- The MRM adjusts the variable-speed blower to maintain a unidirectional flow of air from the room through the hood and via a connecting hose to the polaro graphic oxygen-sensing cell.

Polarographic O_2 Method



$V_M = V_R + V_E - V_I$

V_M = Blower Discharge Rate

V_R = Room Air Entry Rate

V_I = Patient Inhalation Rate

V_E = Patient Exhalation Rate

F_RO_2= Fractional room air O2 content = 0.209

F_MO_2 = Fractional content of O2 flowing past polaro graphic cell

$V_{O2} = (F_RO_2 \times V_R) - (F_MO_2 \times V_M)$

$V_{O2} = V_M (0.209 - F_MO_2) + 0.209 (V_I - V_E)$

Servocontrolled system adjusts VM to keep fractional O2 content of air moving past polarographic sensor (FMO2) at 0.199

Respiratory quotient
RQ = $V_I / V_E = 1.0$

$V_{O2} = 0.01 (V_M) + 0.209 (V_I - V_E)$

$$V_{O2} = 0.01 (V_M)$$

Fick Oxygen Method: A V O_2 difference

Sampling technique

- Mixed venous sample
  - Collect from pulmonary artery
  - Collection from more proximal site may result in error with left-right shunting
- Arterial sample
  - Ideal source: pulmonary vein
  - Alternative sites: LV, peripheral arteria.If arterial desaturation ($SaO2 < 95\%$) present, right-to-left shunt must be excluded

Measurement

- Reflectance (spectophotometric analysis) oximetry

Step 1: Theoretical oxygen carrying capacity

O_2 carrying capacity (mL O_2 / L blood) =

1.36 mL O_2 / gm Hgb x 10 mL/dL x Hgb (gm/dL)

Step 2: Determine arterial oxygen content

Arterial O_2 content = Arterial saturation x O_2 carrying capacity

Step 3: Determine mixed venous oxygen content

Mixed venous O_2 content = MV saturation x O_2 carrying capacity

Step 4: Determine A-V O_2 oxygen difference

AV O_2 difference = Arterial O2 content - Mixed venous O_2 content

Cardiac Output Measurement by Fick Oxygen Method

Total error ≈ 10%

- Error in O2 consumption ≈ 6%
- Error in AV O2 difference ≈ 5%. Narrow AV O2 differences more subject to error, and therefore Fick method is most accurate in low cardiac output states

Sources of Error

- Incomplete collection of expired air (Douglas bag)
  - Underestimate O2 consumption and CO
- Respiratory quotient = 1
  - Volume of CO2 expired is not equal to O2.

Sources of Error

- Spectophotometric determination of blood oxygen saturation

- Changes in mean pulmonary volume
  - Douglas bag and MRM measure amount of O2 entering lungs, not actual oxygen consumption
  - Patient may progressively increase or decrease pulmonary volume during sample collection.

- Improper collection of mixed venous blood sample
  - Contamination with PCW blood
  - Sampling from more proximal site

Does VO_2 actually need to be measured

- Technical difficulties, expense
- Assumption that O_2 consumption can be predicted from BSA.
- Resting O_2 consumption- 125 ml/m² or 110 ml/m² for elderly patients.
- 180 pts; $VO_2 = \frac{\text{CO (indicator dilution technique)}}{\text{A V oxygen difference}}$

126±26 ml/mt/m²

Cardiac Output Measurement -Indicator Dilution Method- ‘Stewart’

Requirements

- Bolus of indicator substance(non toxic) which mixes completely with blood and whose concentration can be measured
- Indicator is neither added nor subtracted from blood during passage between injection and sampling sites
- Most of sample must pass the sampling site before recirculation occurs
- Indicator must go through a portion of circulation where all the blood of the body becomes mixed.

Cardiac Output Measurement

Indicator Dilution Methods

Stewart-Hamilton Equation

$$CO = \frac{\text{Indicator amount}}{\int_0^\infty C(t)\,dt}$$

C = concentration of indicator

$$CO = \frac{\text{Indicator amount (mg)} \times 60\text{ sec}}{\text{mean indicator concentration (mg/mL)} \times \text{curve duration}}$$

- Indicators
  - Indocyanine Green
  - Thermodilution (Indicator = Cold)

Stewart-Hamilton Equation

$$CO = \frac{\text{Indicator amount (mg)} \times 60 \text{ sec}}{\text{mean indicator concentration (mg/mL)} \times \text{curve duration}}$$

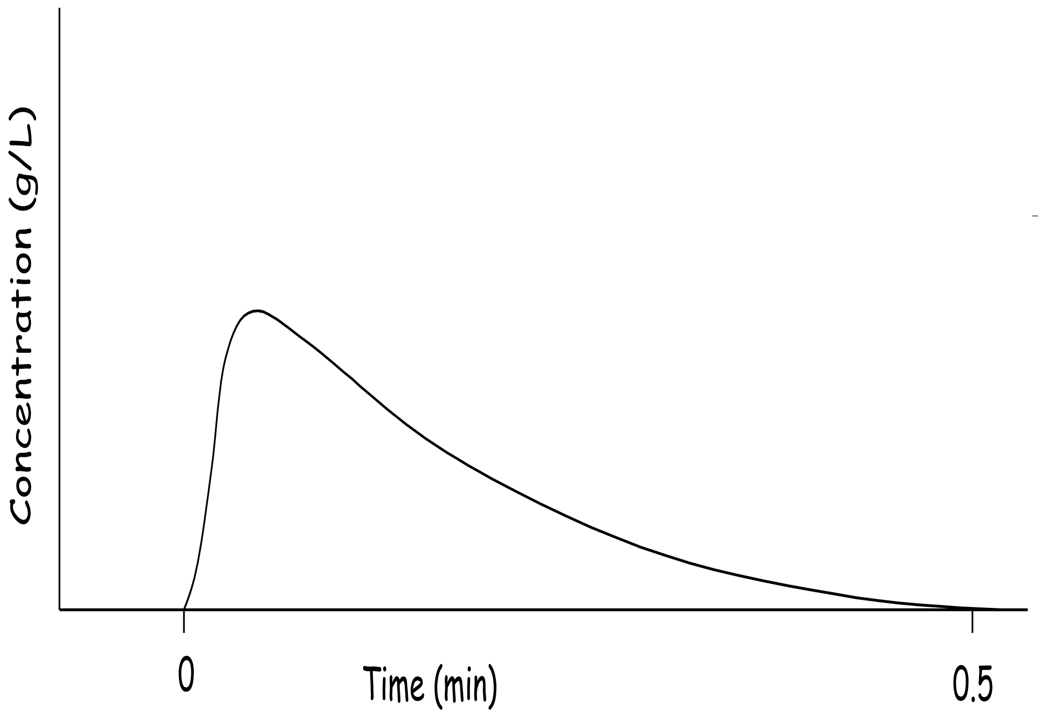
Indicators

- Indocyanine Green
- Thermodilution (Indicator = Cold)

- Indocyanine green (volume and concentration fixed) injected as a bolus into right side of circulation (pulmonary artery)
- Samples taken from peripheral artery, withdrawing continuously at a fixed rate
- Indocyanine green concentration measured by densitometry

Errors in Indocyanine Green Method

- Unstable over time.
- Must be introduced rapidly as single bolus
- Indicator must mix thoroughly with blood, and should be injected just proximal or into cardiac chamber
- Dilution curve must have exponential downslope of sufficient length to extrapolate curve.
- Invalid in Low cardiac output states and shunts that lead to early recirculation
- Withdrawal rate of arterial sample must be constant



- Amount of dye added = 5 mg
- Average dye concentration = 2 mg/L
- Therefore the volume that diluted the dye = 5mg/2mg/L = 2.5 L
- Time took to go past = 0.5 min ie flow rate = 2.5 L /0.5 min = 5

$$\text{Flow rate} = \frac{\text{mass of dye (Q g)}}{\text{Average dye conc (X g/L)} \times \text{time of passage } (\Delta t \text{ min})}$$

~

Thermodilution Method

- Fegler 1954 (CONSERVATION OF ENERGY)

- Cold saline or 5% D
- Balloon-tipped flow-directed pvc catheter
- Thermistor at tip
- Opening 25 to 30 cm proximal to the tip
- Via vein to PA (proximal opening –SVC or RA, thermistor –PA)
- 5 to 10 mL to proximal port
- Change in temperature at the thermistor recorded

Cardiac Output Measurement

Thermodilution Method

$$CO = \frac{V_I\,(T_B - T_I)\,(S_I \times C_I \,/\, S_B \times C_B)\times 60 \times 0.825}{\int_0^{\infty} \Delta T_B \, dt}$$

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

0.825-correction factor for warming of injectate from the syringe or by catheter

Advantages over indo cyanine green dye method

- Withdrawal of blood not necessary
- Arterial puncture not required
- Indicator (saline or D5W)- inert and inexpensive.
- Virtually no recirculation, simplifying computer analysis of primary curve sample

Sources of Error

- 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

Pitfalls Of CO Measurement

FICK'S METHOD

- Inadequate mixing of blood in RA
- Inappropriate sampling
- Contamination of blood with air, hep saline.
- VO_2-not usually measured.
- Improper measurement of VO_2
- High output states with narrow A V O_2 difference

THERMODILUTION METHOD

- Low output states *(incomplete mixing of indicator)*
- AF *(incomplete mixing of indicator)*
- TR *(indicator abnormally recirculated)*
- Intra cardiac shunts *(indicator abnormally recirculated)*
- Administration of IVF simultaneously

Conclusion

- Pressure is force per unit area.
- Optimal damping is important to prevent errors in pressure measurement.
- In Low cardiac output states, fick’s method is more reliable.
- In high cardiac output states, thermo dilution method is reliable.
- In PR, TR and intra cardiac shunts, thermo dilution is not reliable.