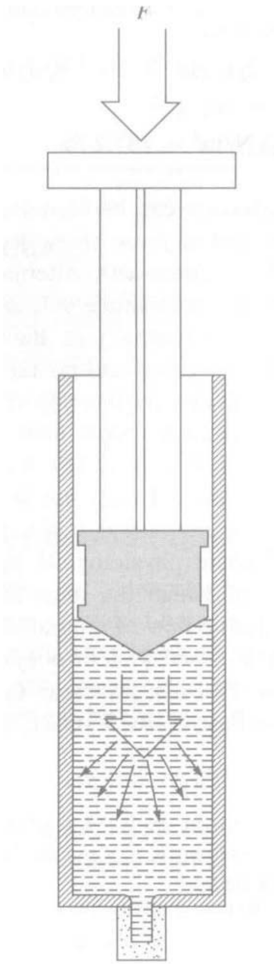
Blood Pressure and Sound

What is pressure?

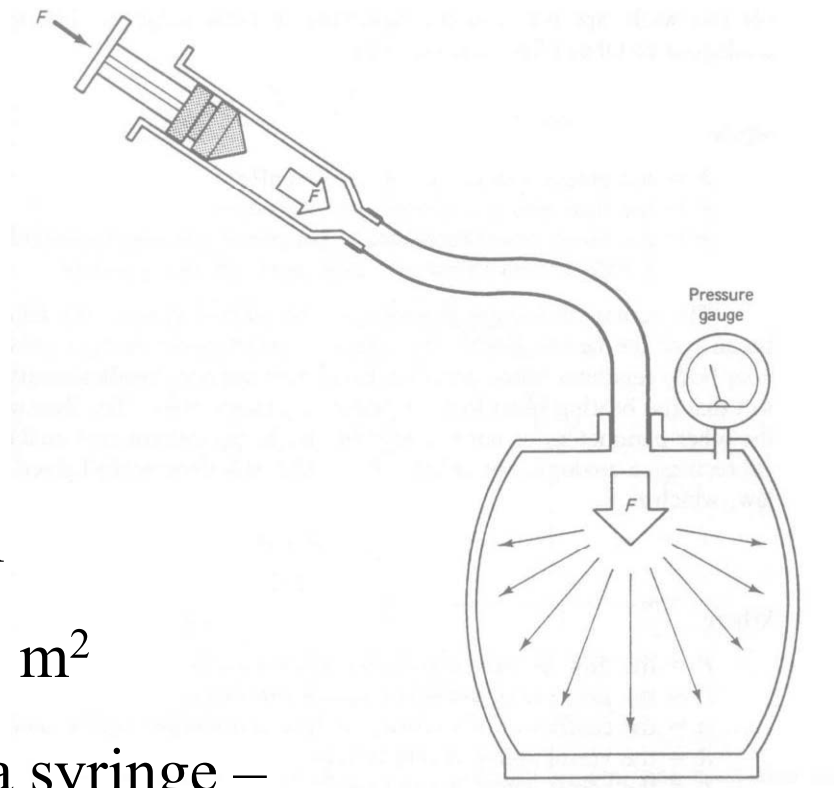


$$P=F/A$$

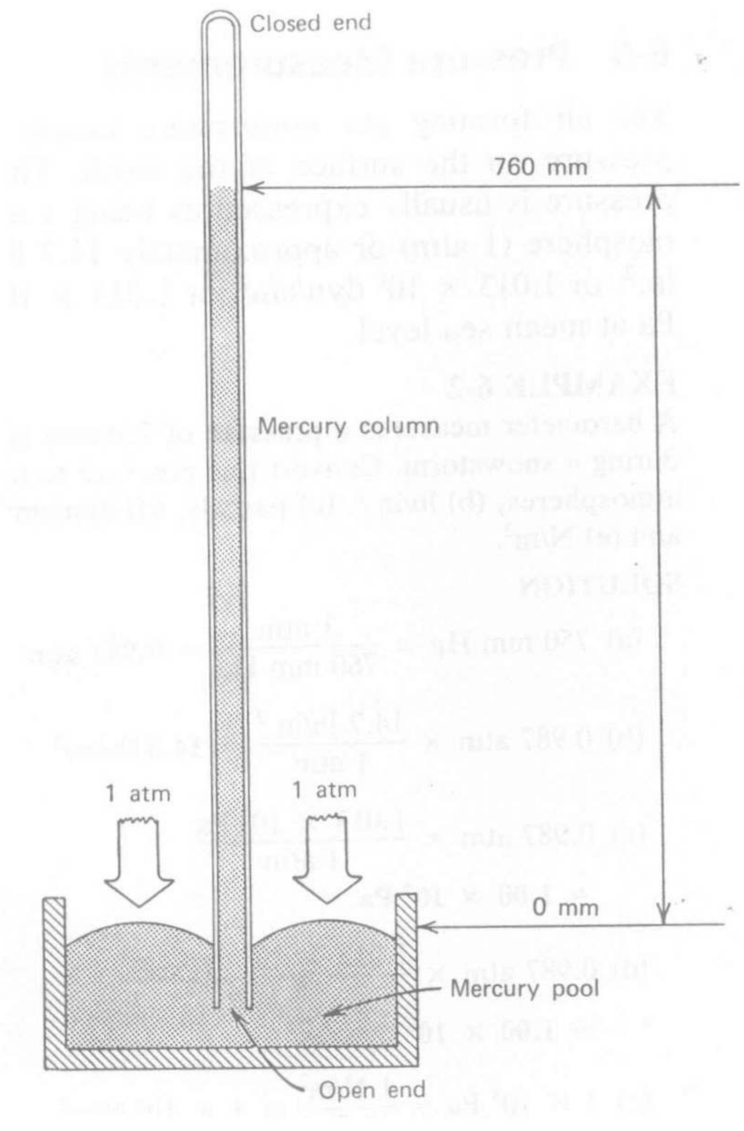
-Measured in Pascal

-1 Pa = 1 Newton/ 1 m^2

-Sectioned view of a syringe – pressure exerted by plunger is distributed to all parts of the fluid



Measurement of Pressure



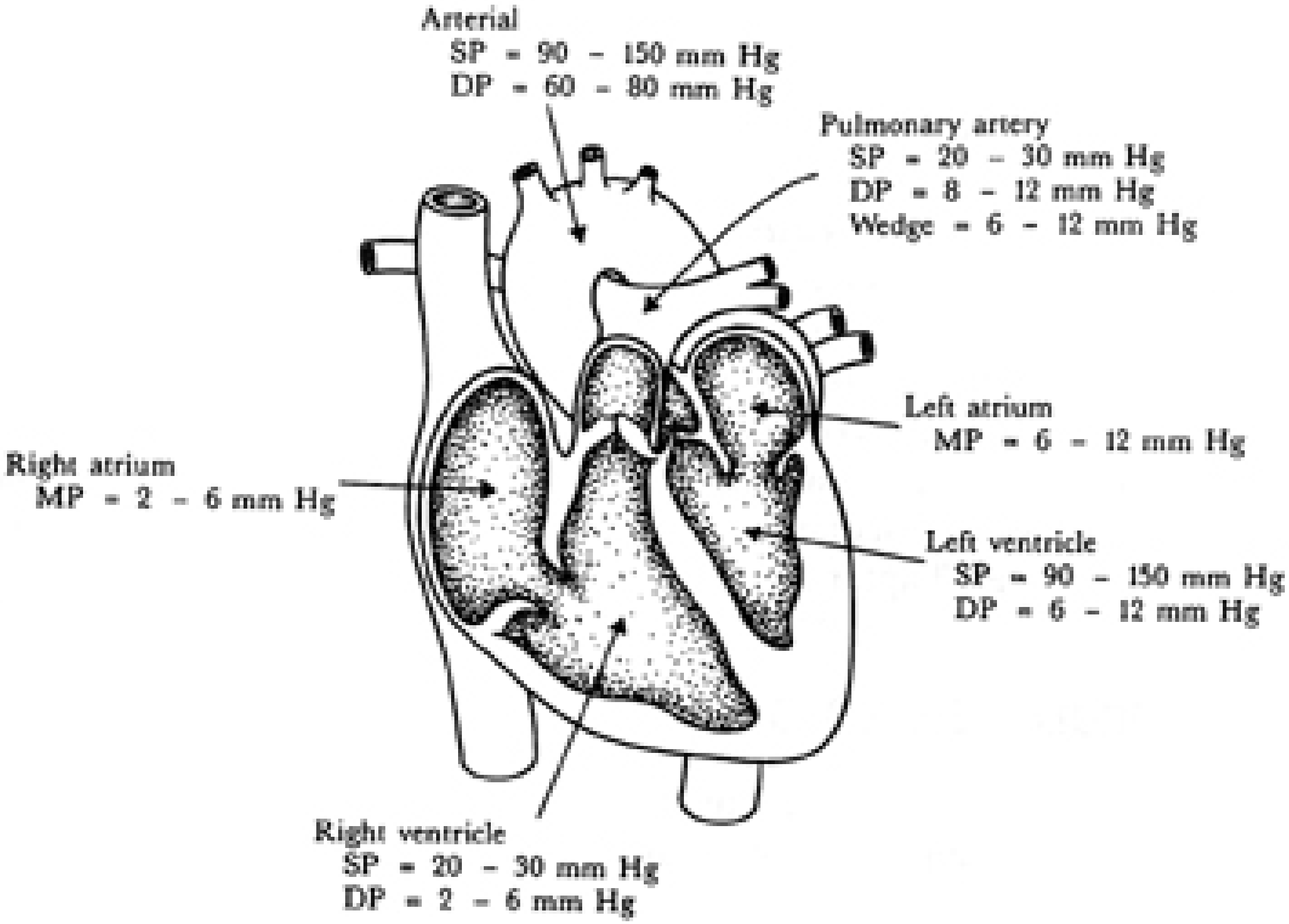
-1 Atmosphere = force needed to raise the mercury in column about 760 mm high

-Blood pressure is measured in terms of mm Hg

Why we measure pressure?

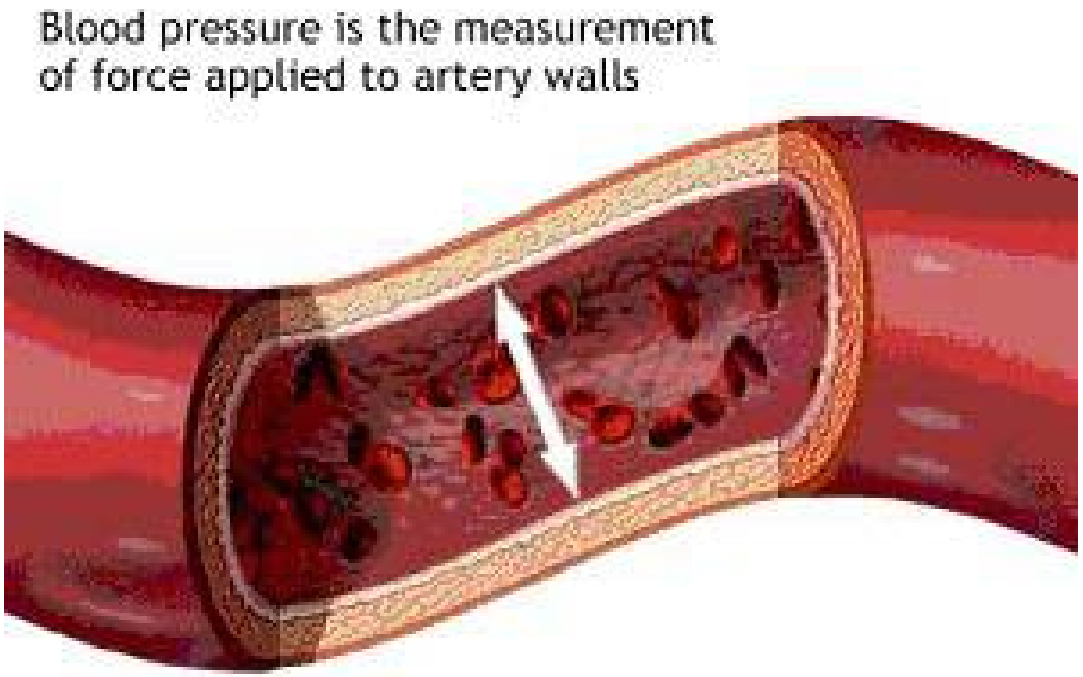
- Pressure is the driving force of the dynamics of the human body
- Pressure is generated by the heart (constant volume or a constant pressure pump?)
- Changes of the pressure inside heart chambers cause acceleration and deceleration of the blood that generate sounds.

Blood Pressure around the Heart



Blood pressure reading as essential of every clinical visit

Arterial blood pressure



Very direct measurement of blood pressure

Direct measurements

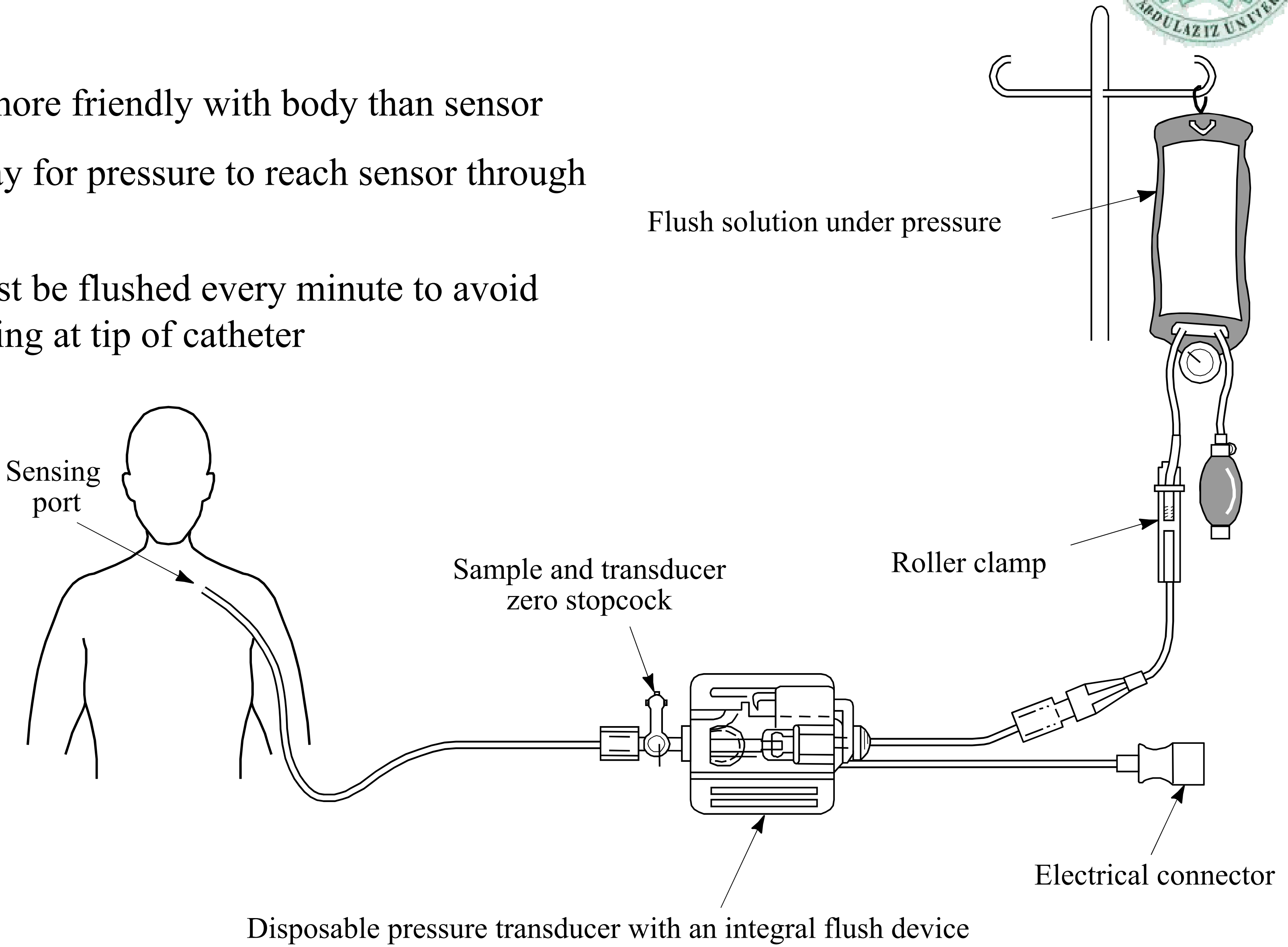
- Extra-vascular sensors:
  - Catheter filled with saline-heparin solution connected to a sensor.
  - Connected to the vessel through surgical cut-down or percutaneous insertion
- Sensors used can be:
  - Strain gage, piezo-electric crystals, LVDT, variable inductance, variable capacitance, opteo-electronics, and semiconductor devices

Direct – Extra Vascular Measurement of Blood pressure

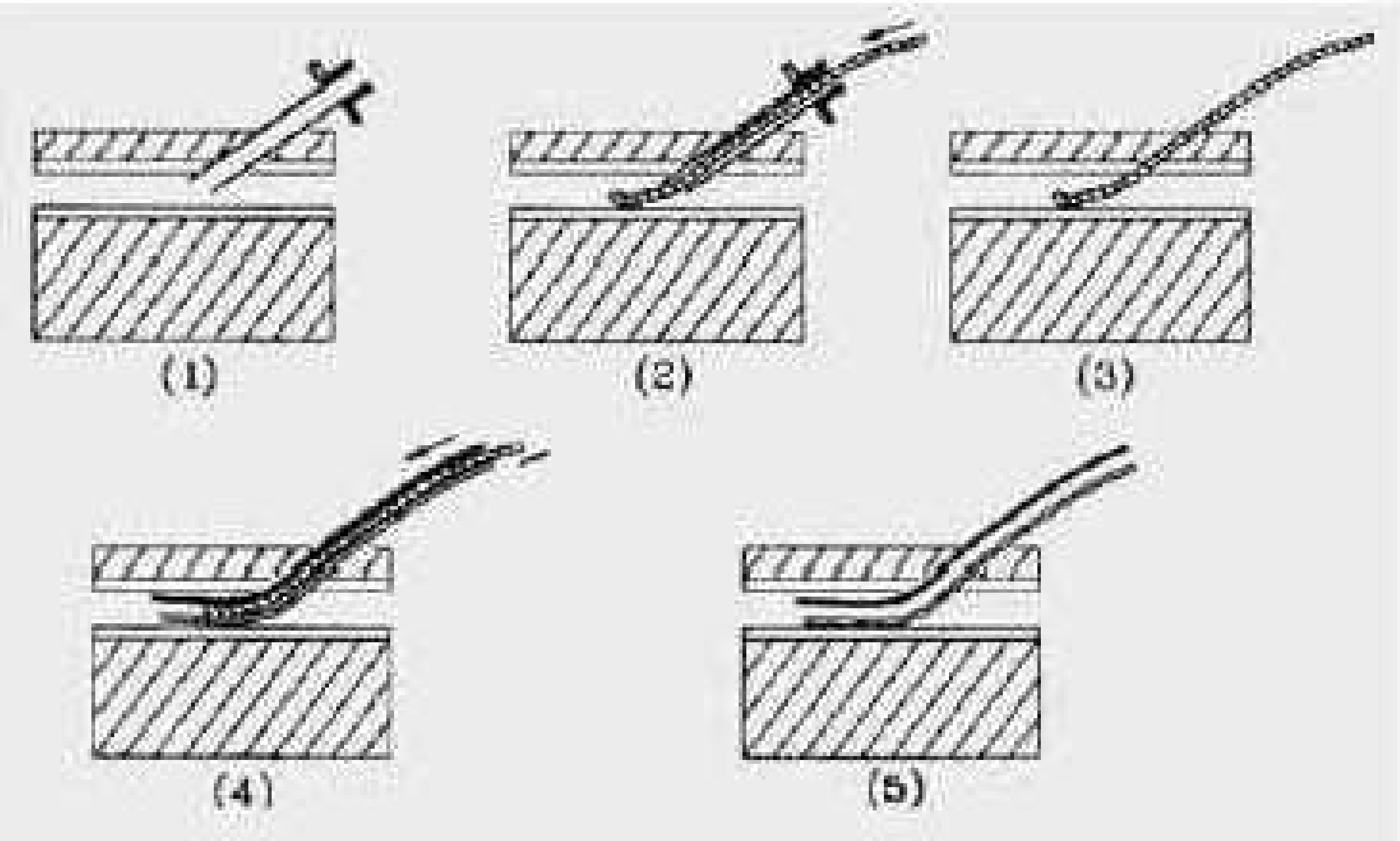
-Saline is more friendly with body than sensor

-Time Delay for pressure to reach sensor through saline

-Saline must be flushed every minute to avoid blood clotting at tip of catheter

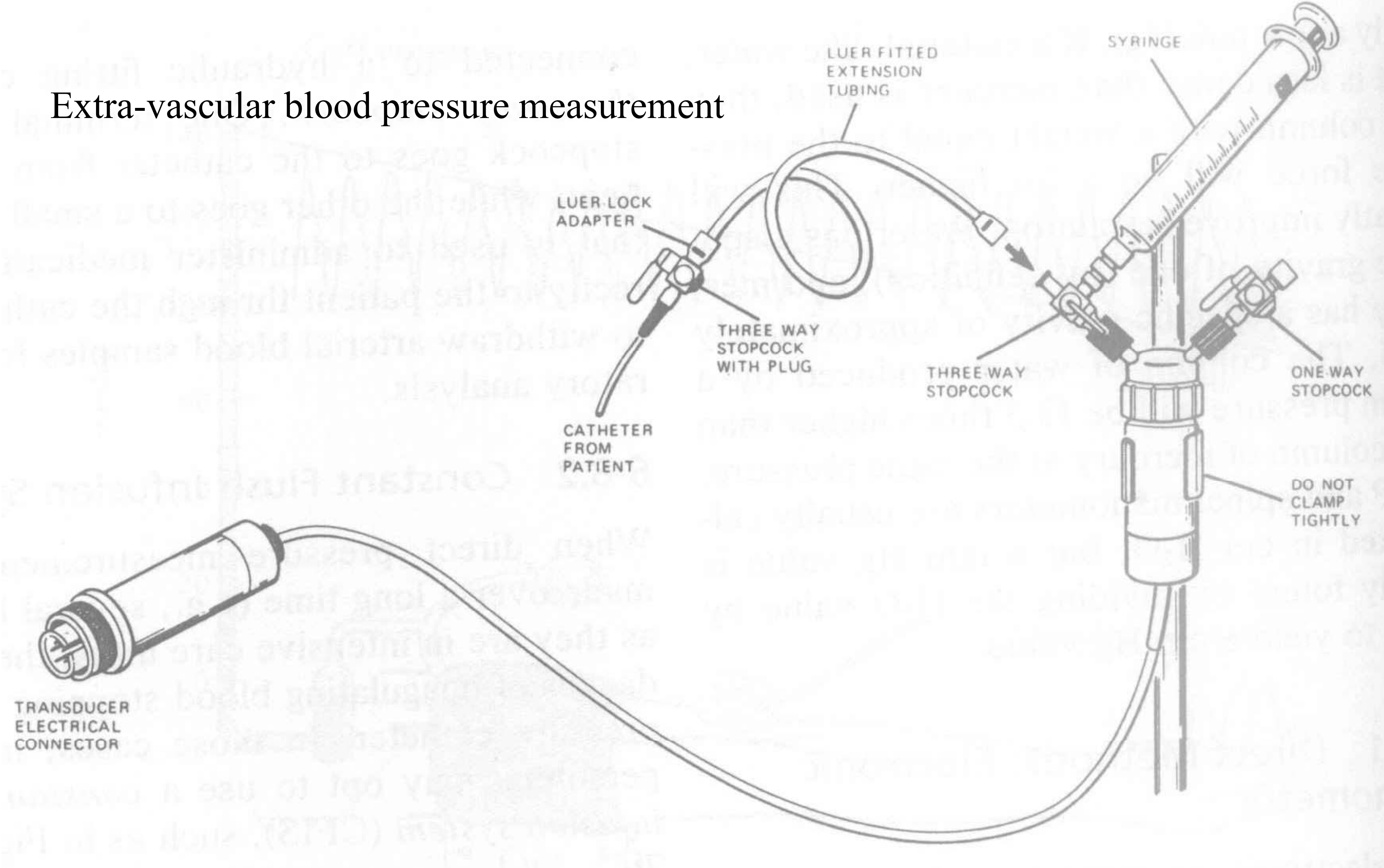


Insertion of catheter: *Seldinger-technique*



An arterial monitoring set-up

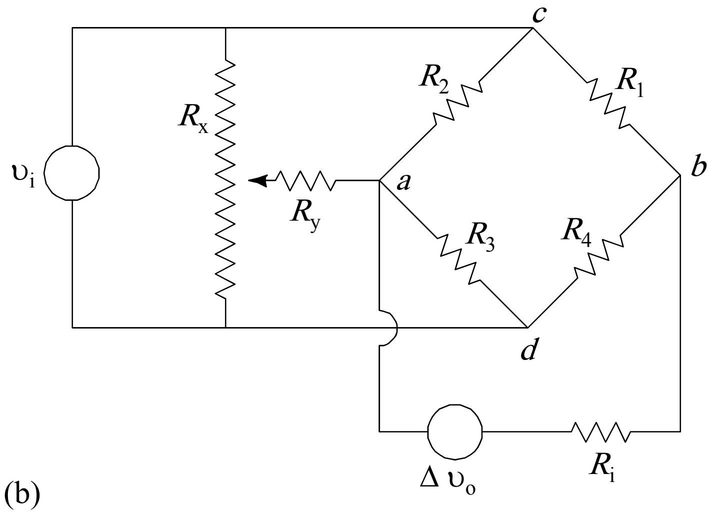
Extra-vascular blood pressure measurement



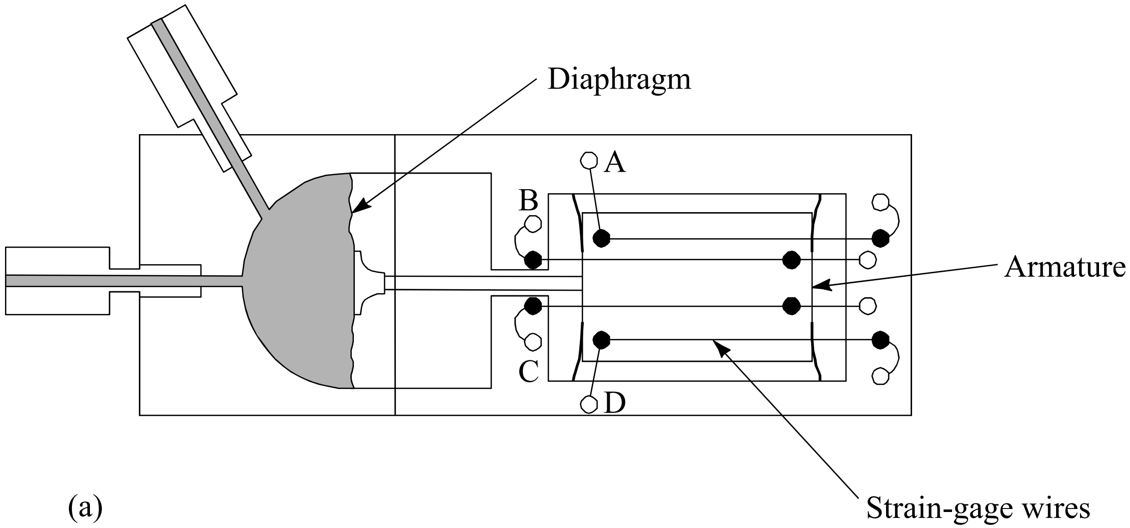
Direct measurements

- Intravascular sensors:
  - Sensors a tip of catheter
  - Has higher frequency response and less time delay
  - More expensive, may break after a few uses
- Sensors used can be:
  - Strain gage, piezo-electric crystals, LVDT, variable inductance, variable capacitance, opteo-electronics, and semiconductor devices

Old Generation Pressure Sensor



(b)

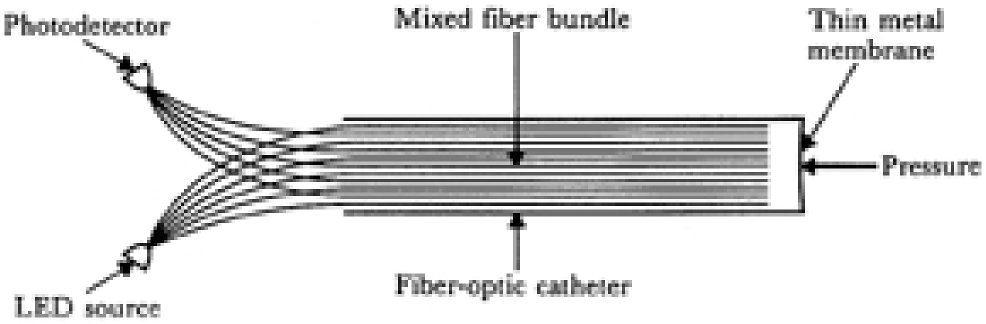


(a)

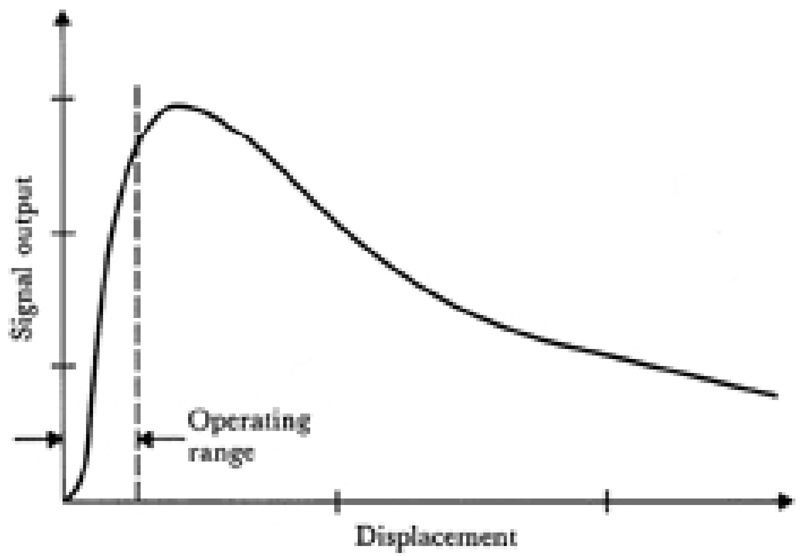
Wheatstone bridge for the pressure sensor (four active elements)

Diaphragm coupled with strain gage, when P increases ➔ strain B &C increases and strain on A&D decreases

Fiber Optics based Pressure Sensor



(a)



(b)

-Operate in linear range of response

-Pressure causes membrane deflection

-Deflection causes change in angle of reflected light

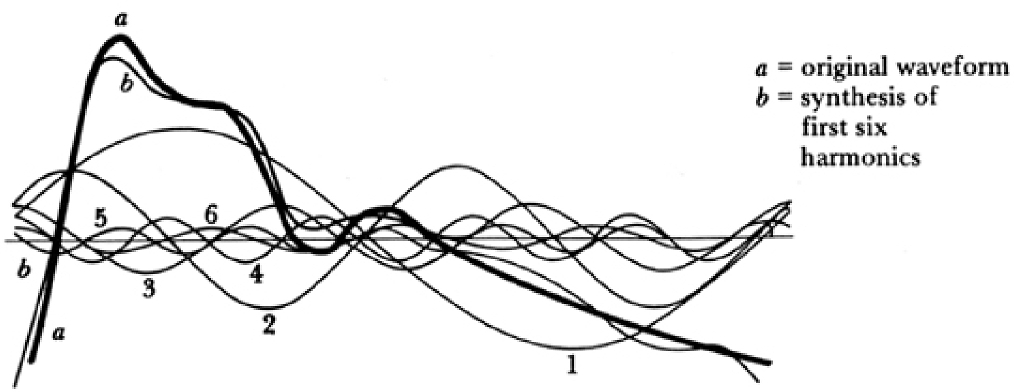
-Reflected light is picked up by Photo-detector

-The amount of reflection is proportional to the membrane motion which is proportional to the blood pressure

Disposable Pressure Sensor

- Connect diaphragm to a piezo-electric crystal
- Pressure moves diaphragm→ crystal moves→ voltage is generated
- Reduce cross-patients contamination
- Can connect diaphragm to variable resistor to measure diaphragm displacement and related to pressure

Harmonic analysis of BP waveform



Harmonic	Amplitude (%)
1	100
2	63.2
3	29.6
4	22.2
5	14.8
6	11.8

- A Pressure waveform can be decomposed into infinite number of sine waves with different amplitudes and phases
- Adding the first six harmonics almost reconstructs the signal

Required bandwidth for measuring

- Up to 10^{th} harmonics if interest is in the amplitude of the signal
- Up to 20^{th} harmonics if interest is in the slope of the signal (d/dt information)
- Catheter + transducer system must have sufficient bandwidth
- Catheter + transducer system must have suitable dynamic properties

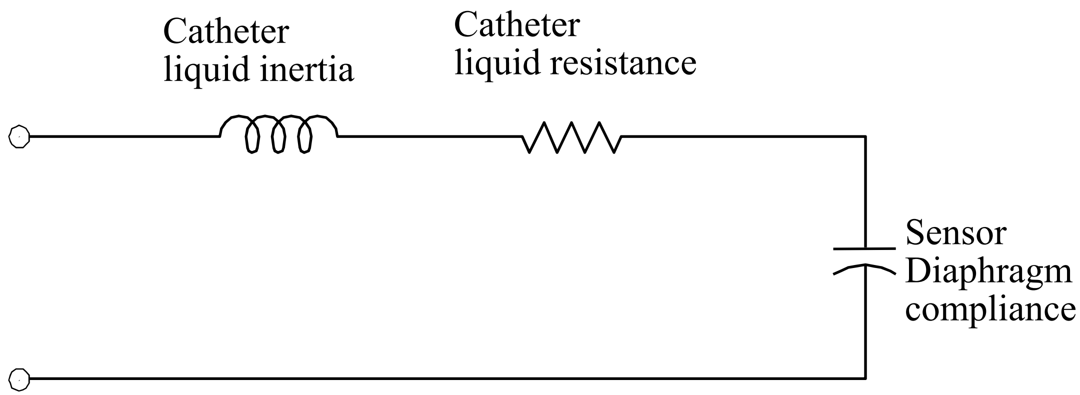
Bandwidth requirements

- For BP waveform: harmonics higher than the 10^{th} are ignored
  - BP BW for HR of 120 bpm is 20 Hz
  - Derivative of BP may require BW up to frequency of the 20^{th} harmonic.

Modeling the catheter-sensor system

- We have three components (diaphragm, sensor and the liquid catheter)
- Each component has
  - Inertial ➔ resistance to motion
  - Friction ➔ touching other material
  - Elasticity➔ Ability to change shape with pressure

The catheter-sensor system No-bubble



- Resistance due to friction between molecules moving in catheter

$$R = \Delta P/F = \Delta P/\mu A$$

  - Where ΔP is pressure difference across a segment in Pa, F is flow rate, m^3/s, μ is the average velocity m/s, and A is the cross sectional area m^2
- Inertia or inertance L_c is given by

$$L_c = \Delta P/(dF/dt) = \Delta P/aA = \rho L/A$$

  - Where a= acceleration of fluid m/s^2, L =Length of catheter, ρ is density of fluid kg/m^3
- Compliance $C = \Delta V/\Delta P = 1/E_d$
  - Where E_d is the modulus of elasticity for the diaphragm

The catheter-sensor system No-bubble

-Solving the second order system

$$I_c(t) = C\frac{dv_o(t)}{dt}$$

$$KVL$$

$$v_i(t) = L\frac{dI_c(t)}{dt} + I_c(t)R + v_o$$

$$v_i(t) = LC\frac{d^2 v_o(t)}{dt^2} + RC\frac{dv_o(t)}{dt} + v_o(t)$$

For a laminar flow

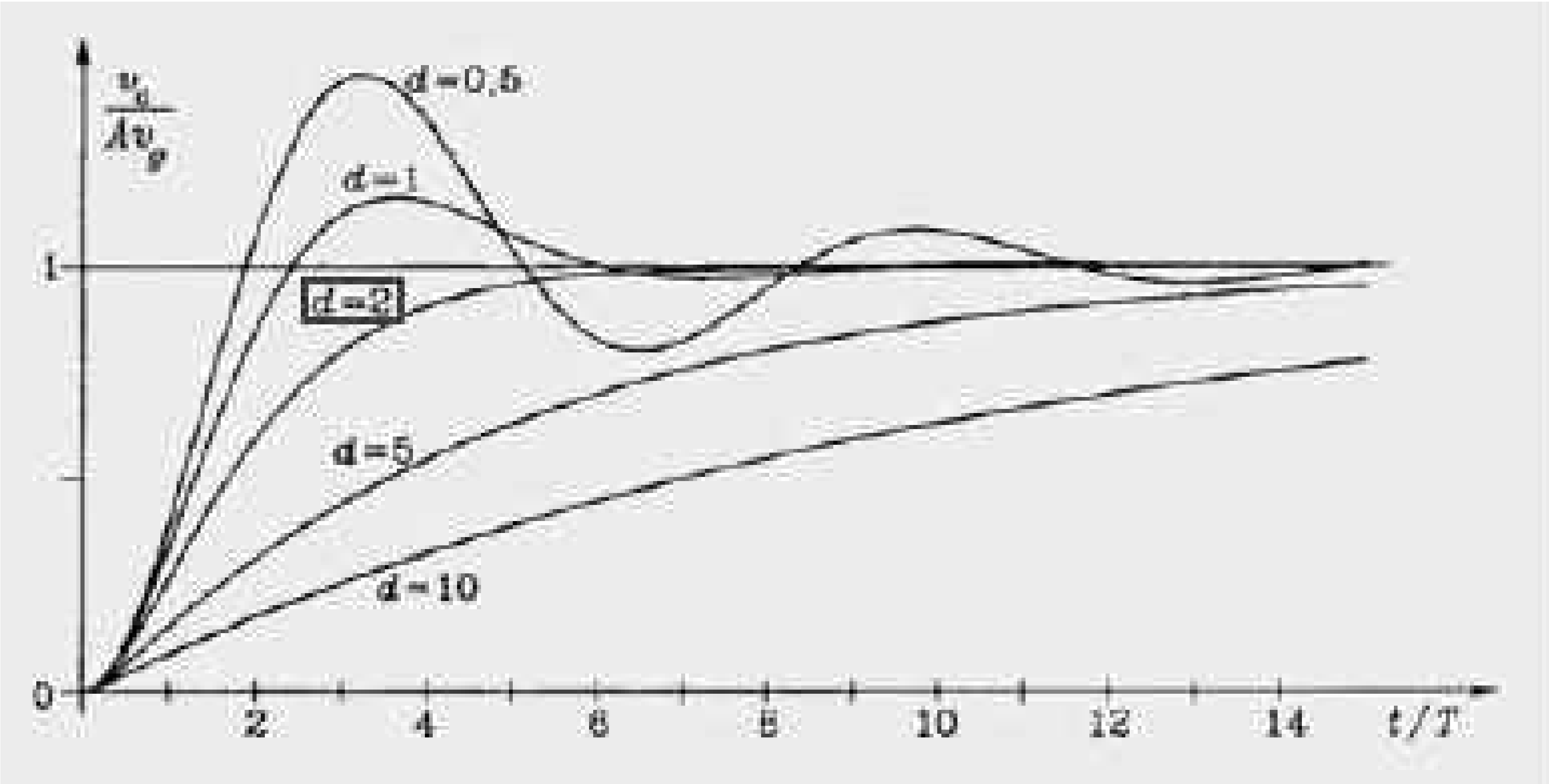
$$f_n = \frac{r}{2}\sqrt{\frac{\Delta P}{\pi\rho L\Delta V}}$$

Resonance Frequency

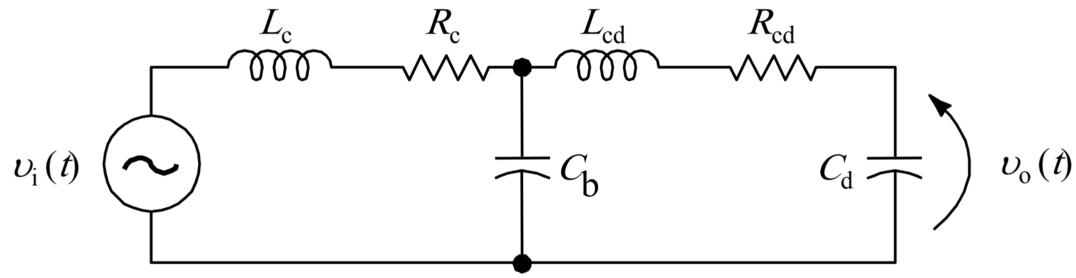
$$\xi = \frac{4\eta}{r^3}\sqrt{\frac{L(\Delta V / \Delta P)}{\pi\rho}}$$

Damping Ratio (η= viscosity)

Normalized step responses (2nd order system)

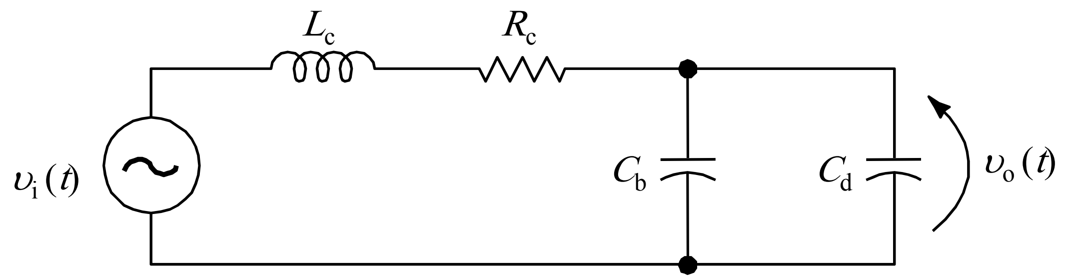


Effect of bubble in system



(b)

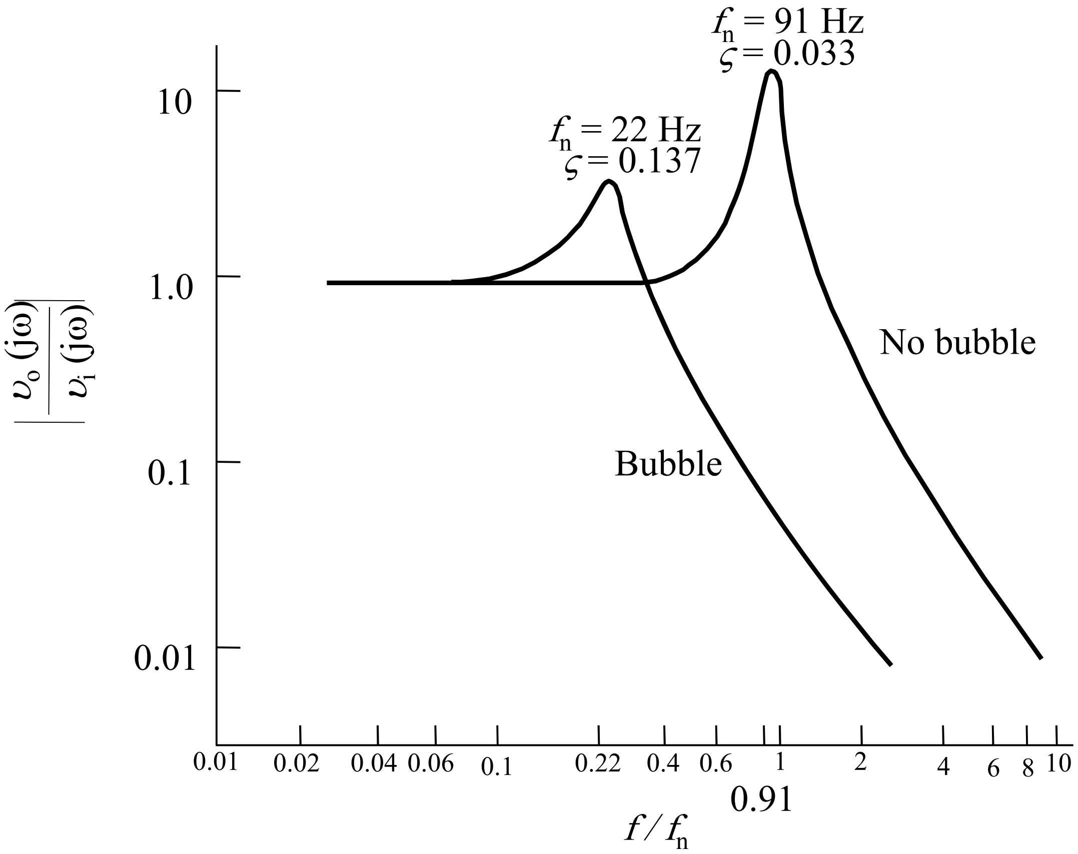
Effect of Bubble



(c)

Two parts, one before the bubble and the other is after the bubble, can ignore some elements

Transfer function with and without air bubble



Bubble reduces cut-off frequency

For proper BP measurement, need to get 20 harmonics ~40Hz

BP terms and concepts

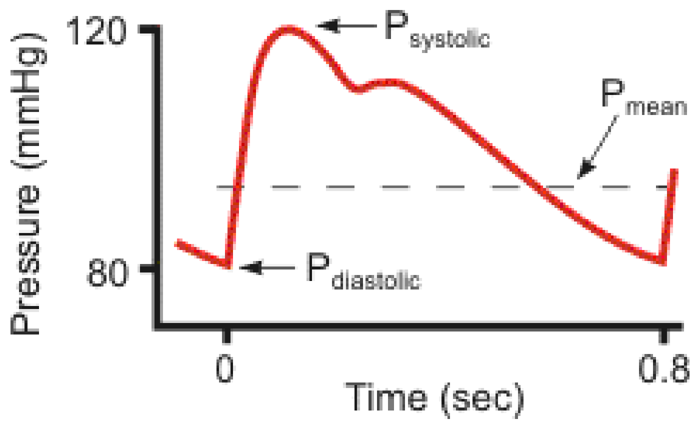
- Heart Rate (HR): Rate at which the heart is pumping blood
- Stroke Volume (SV): volume of blood pumped in one cycle
- Cardiac output (CO): Volume of blood pumped by the heart = HR x SV
- Mean Arterial Pressure (MAP)=$P_{dias}+1/3(P_{sys}-P_{dias})$
- Resistance of vessels (capillaries), required cardiac output, and thickness of blood affect blood pressure
- Exercise ➔ more blood is needed ➔increase CO
- Vessels obstructed ➔ resistance is high ➔ increase BP to force the flow

Modeling the BR

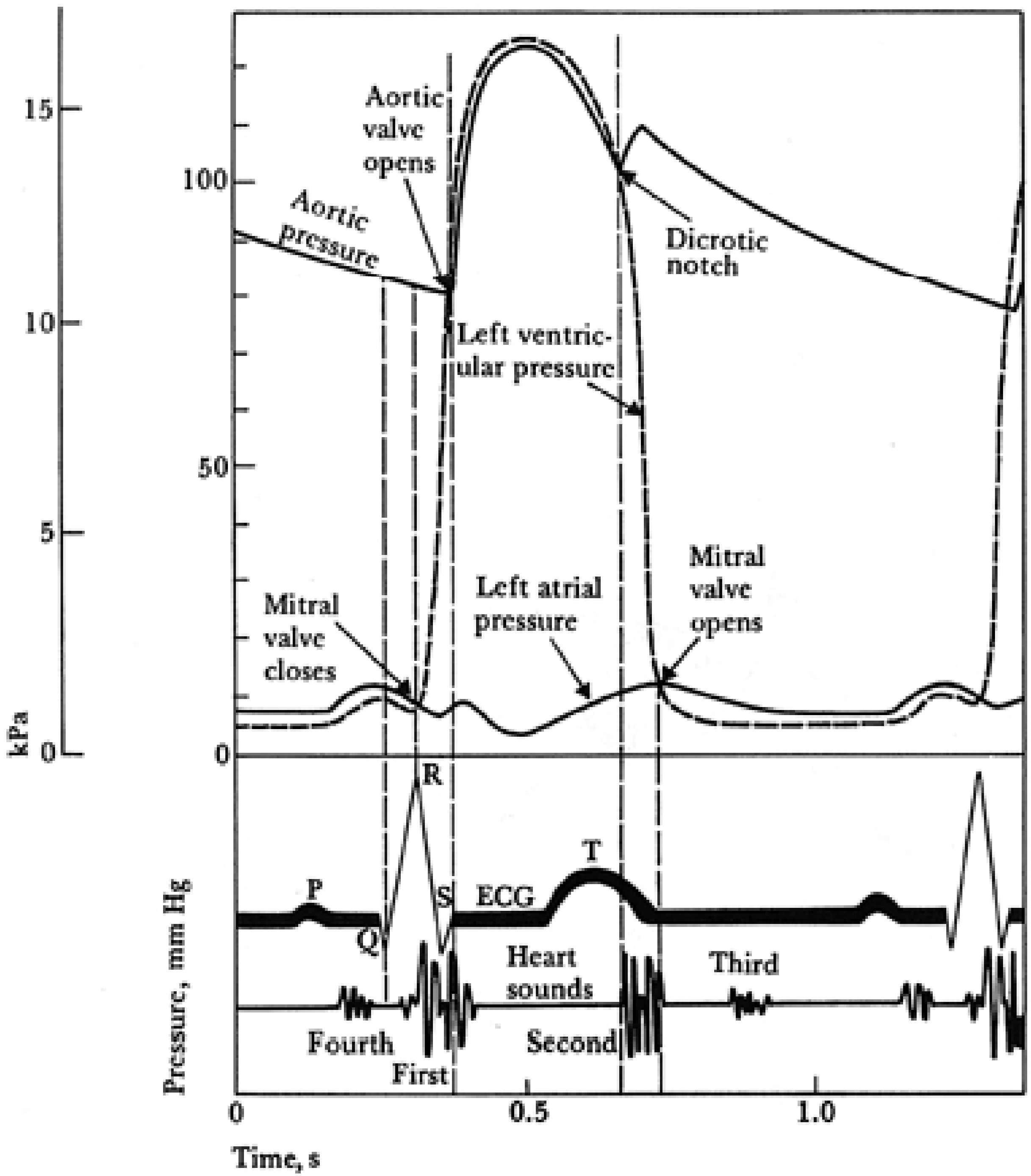
- Blood flow can be modeled using Ohms law where pressure resembles voltage, flow resembles current and resistance of vessels is impedance (resistive + capacitive)
- Many models are there to measure cardiac output using MAP
- R (vessels resistance, L length, r is radius, and P is pressure)

$$(R) \propto \frac{\eta L}{r^4} \qquad F \propto \frac{\Delta \mathrm{P} r^4}{\eta L}$$

BR waveform



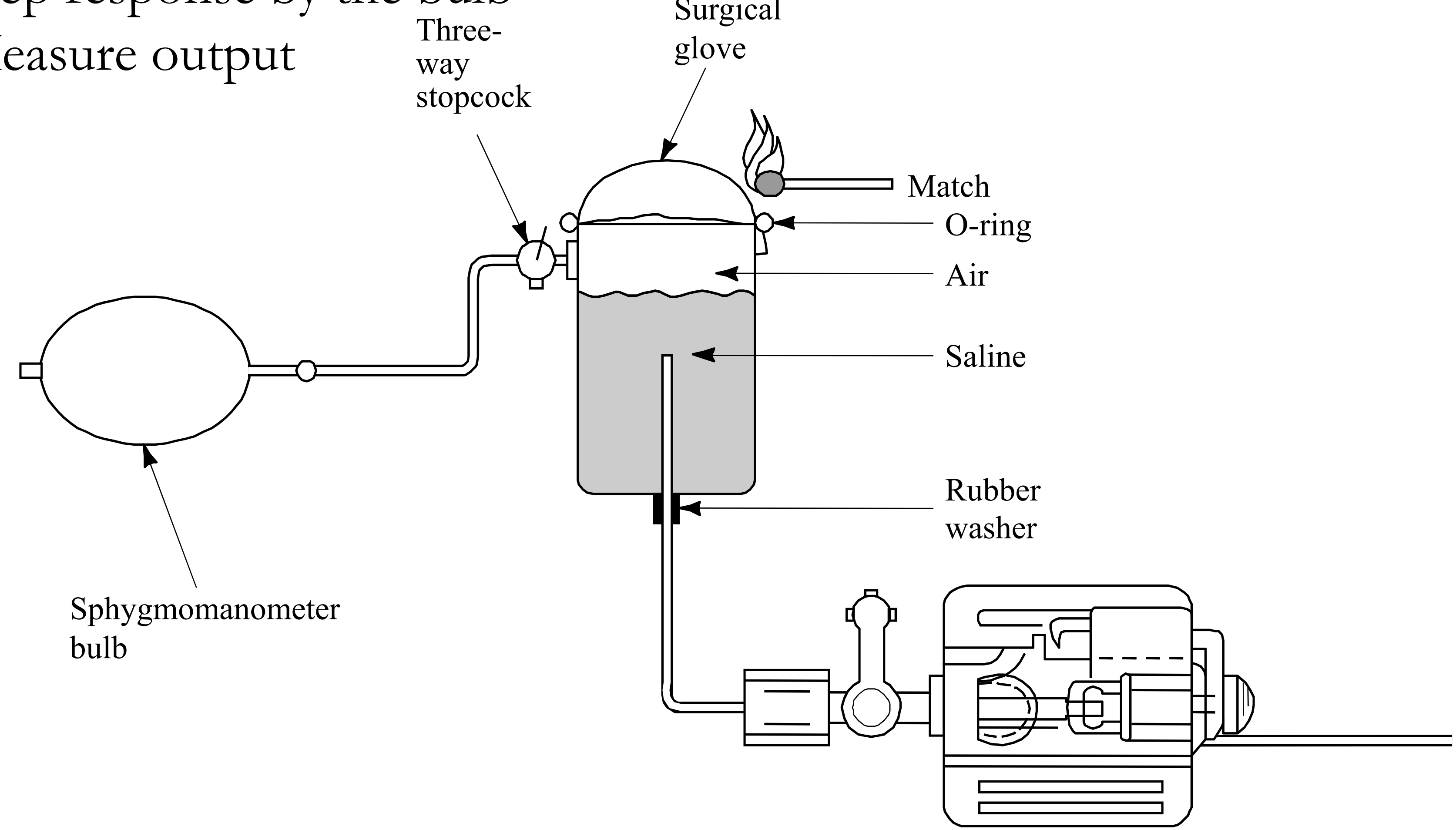
- Systolic pressure ($P_{systolic}$) ➔ ventricle ejects into aorta
- As ventricle relaxes, pressure drops
- The "dicrotic notch,“ occurs with aortic valve closes
- Lowest value before blood ejection is $P_{diastolic}$



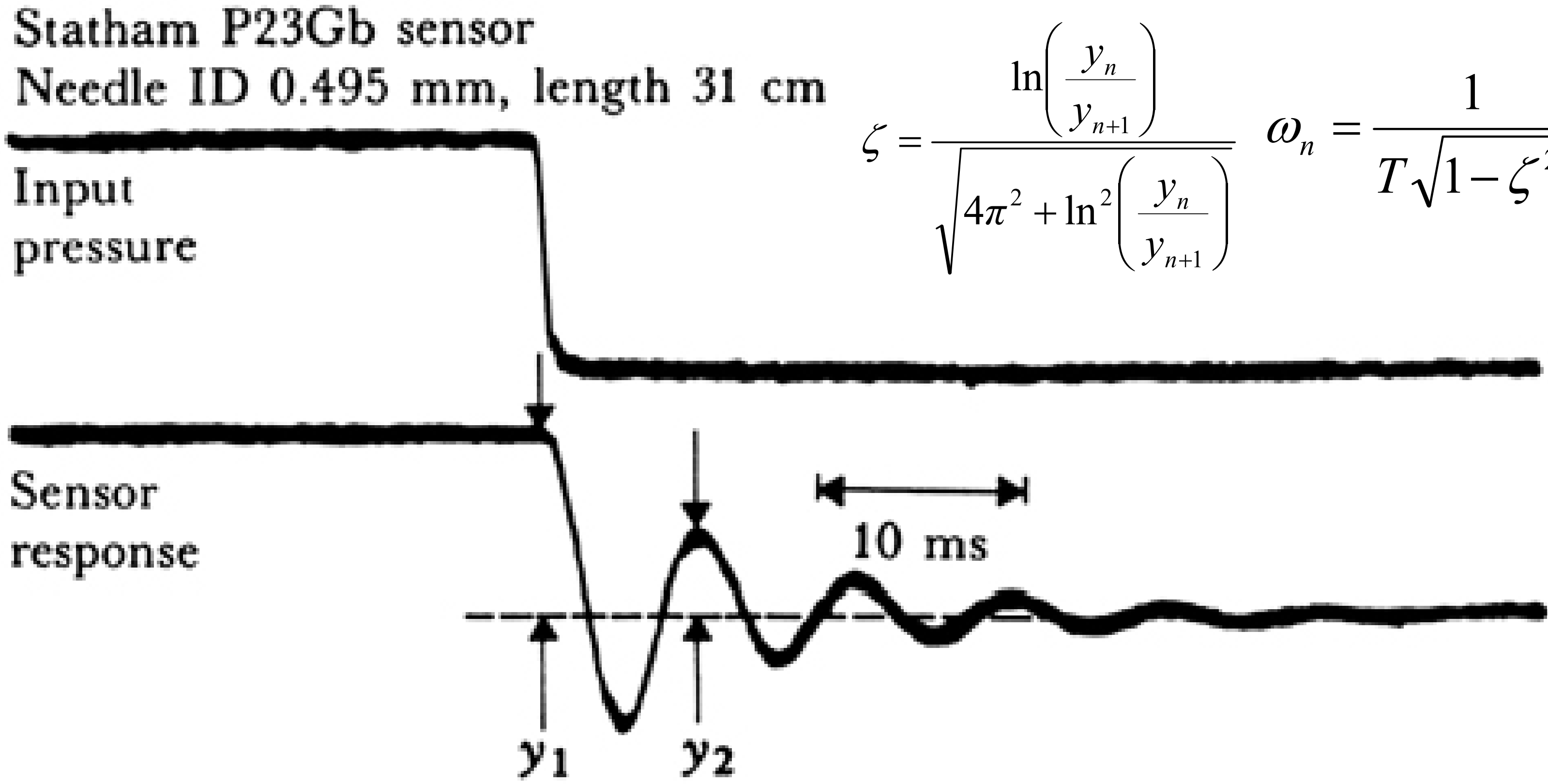
Pressure in and around the heart

System step response

Step response by the bulb
Measure output



Step response

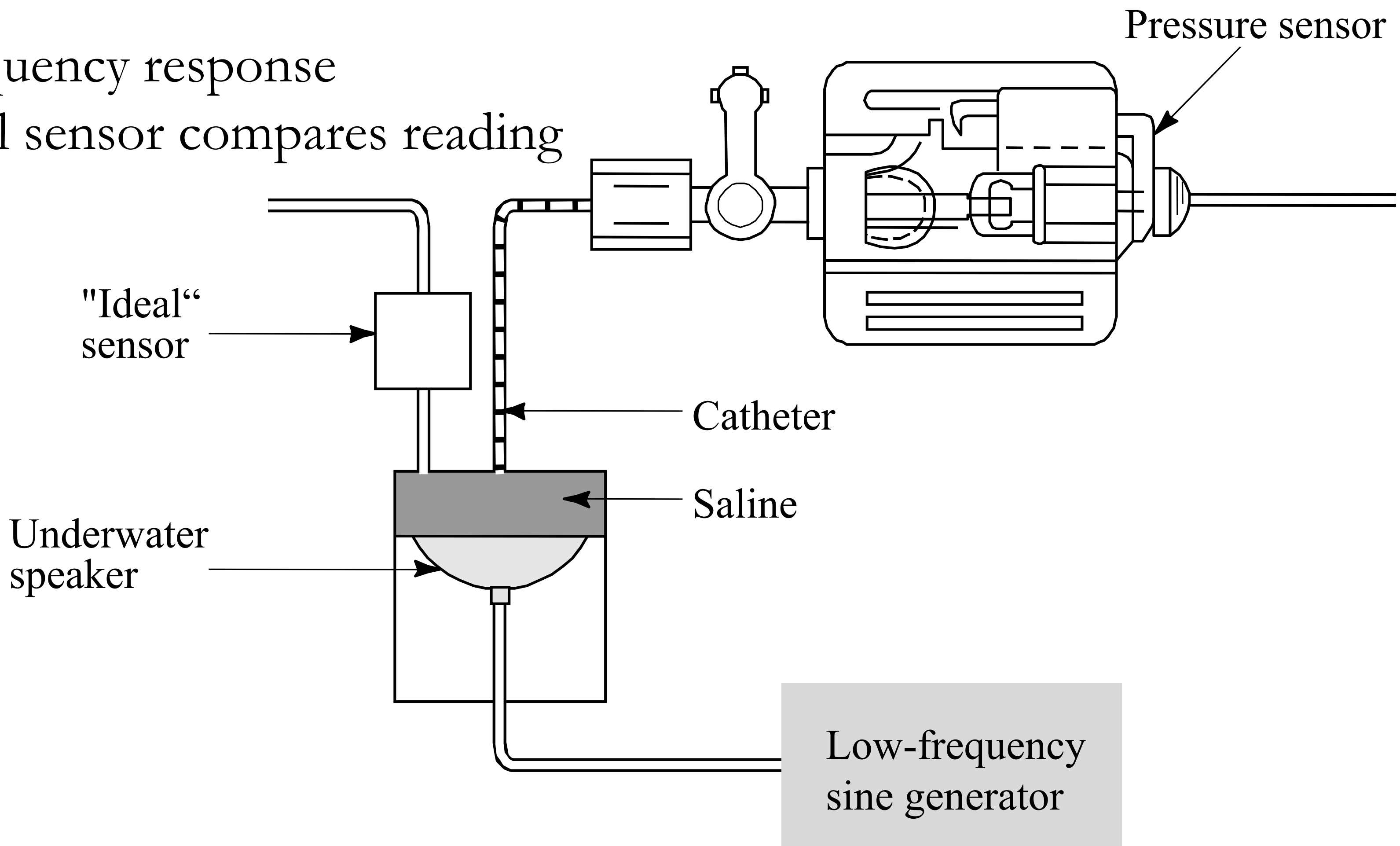


$$\zeta = \frac{\ln\left(\frac{y_n}{y_{n+1}}\right)}{\sqrt{4\pi^2 + \ln^2\left(\frac{y_n}{y_{n+1}}\right)}} \quad \omega_n = \frac{1}{T\sqrt{1-\zeta^2}}$$

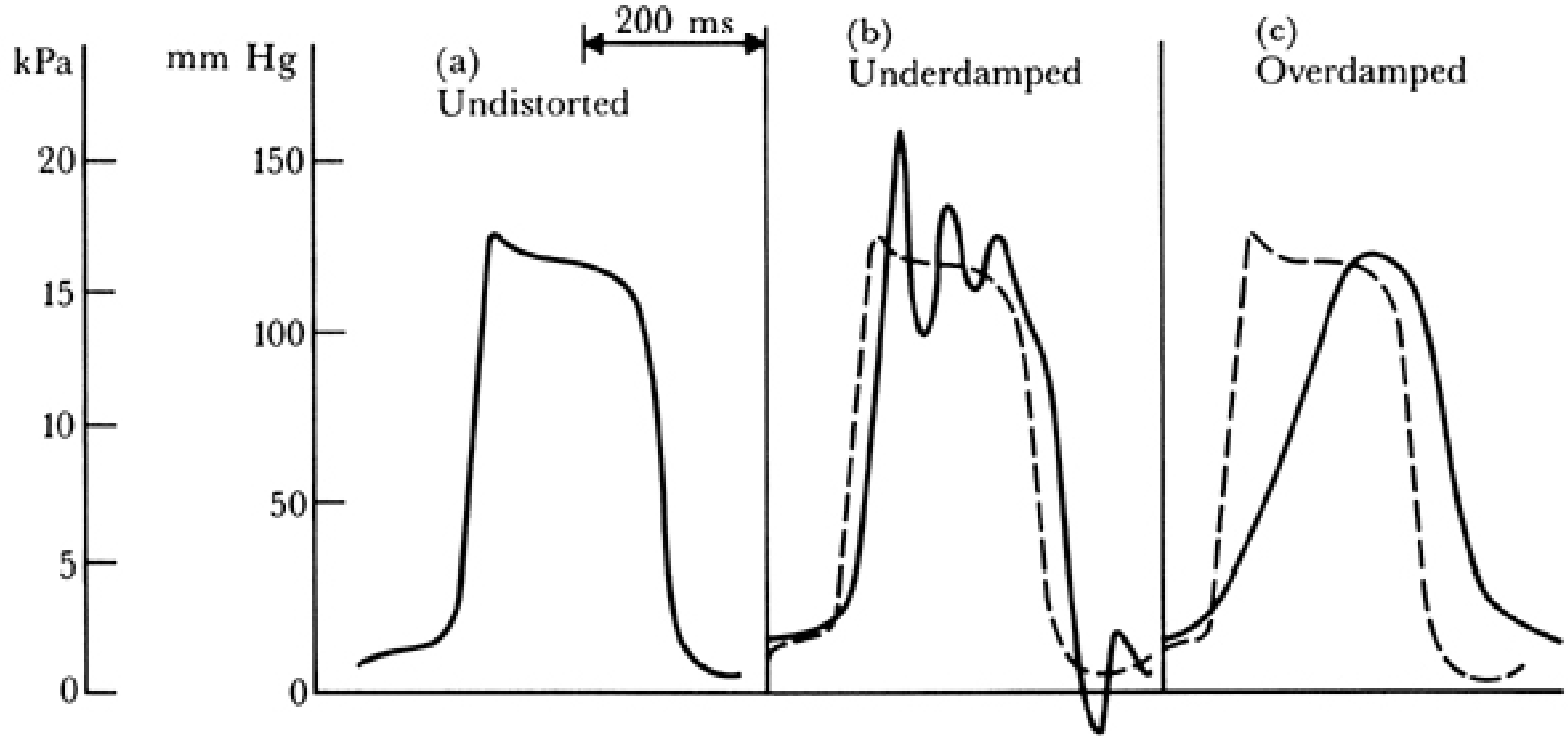
Sinusoidal Response (frequency)

Frequency response

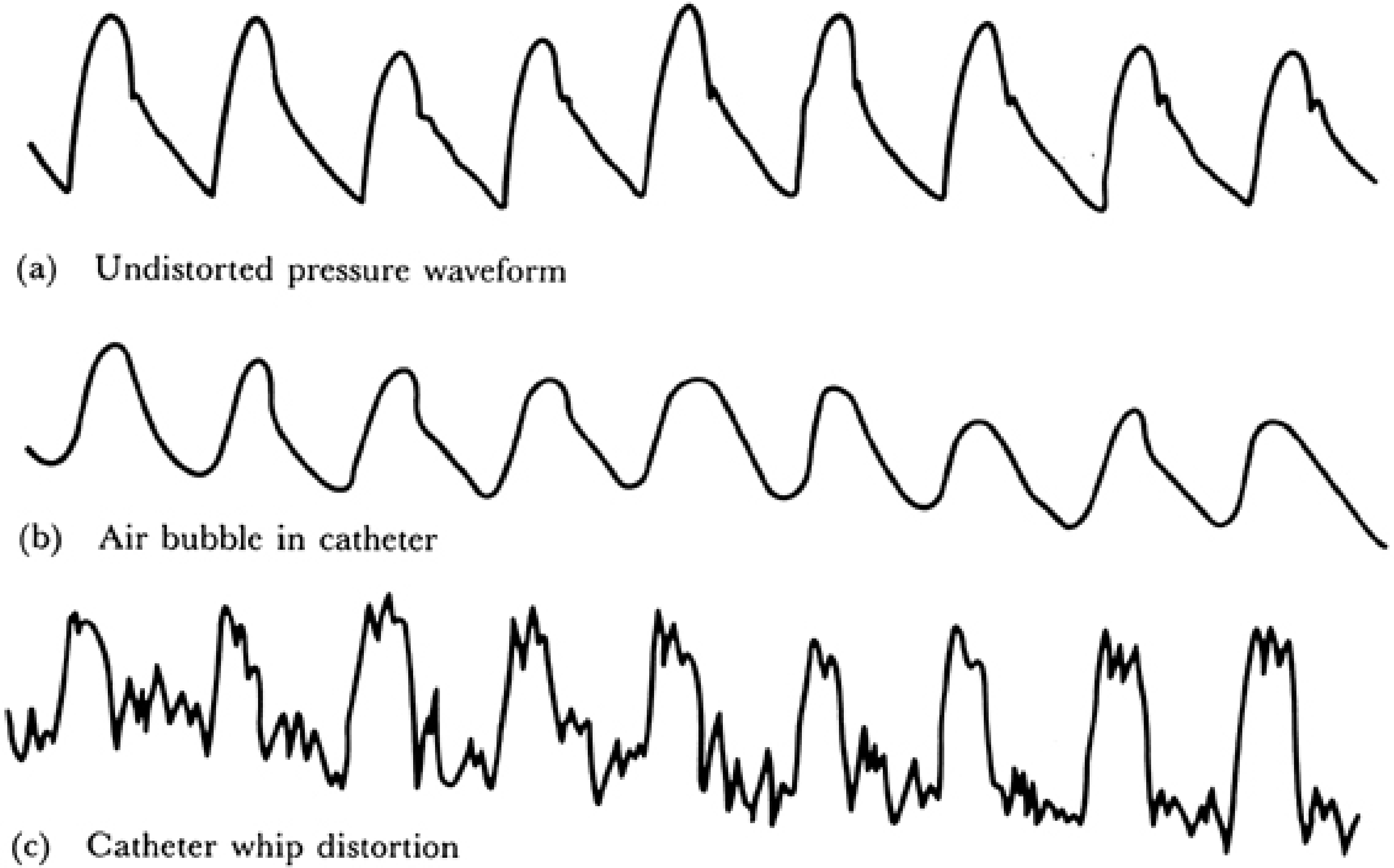
Ideal sensor compares reading



Waveform distortion

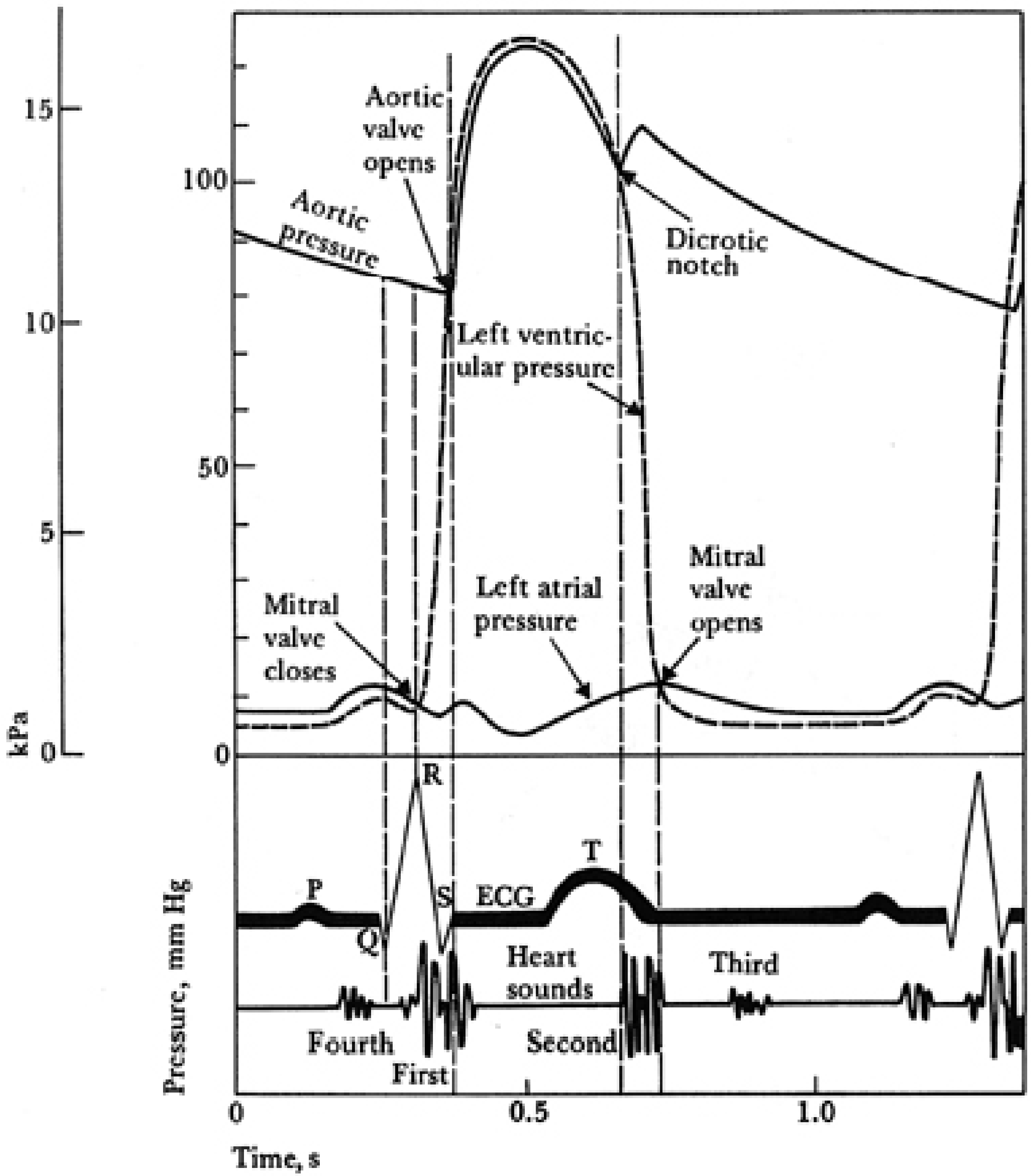


Waveform distortion



Heart sounds

- Sounds: due to acceleration and deceleration of the blood.
- Murmurs: due to blood turbulence



Heart sounds:

1st: closing mitral and tricuspid valves

2nd: closing of aortic valve (end of ECG T)

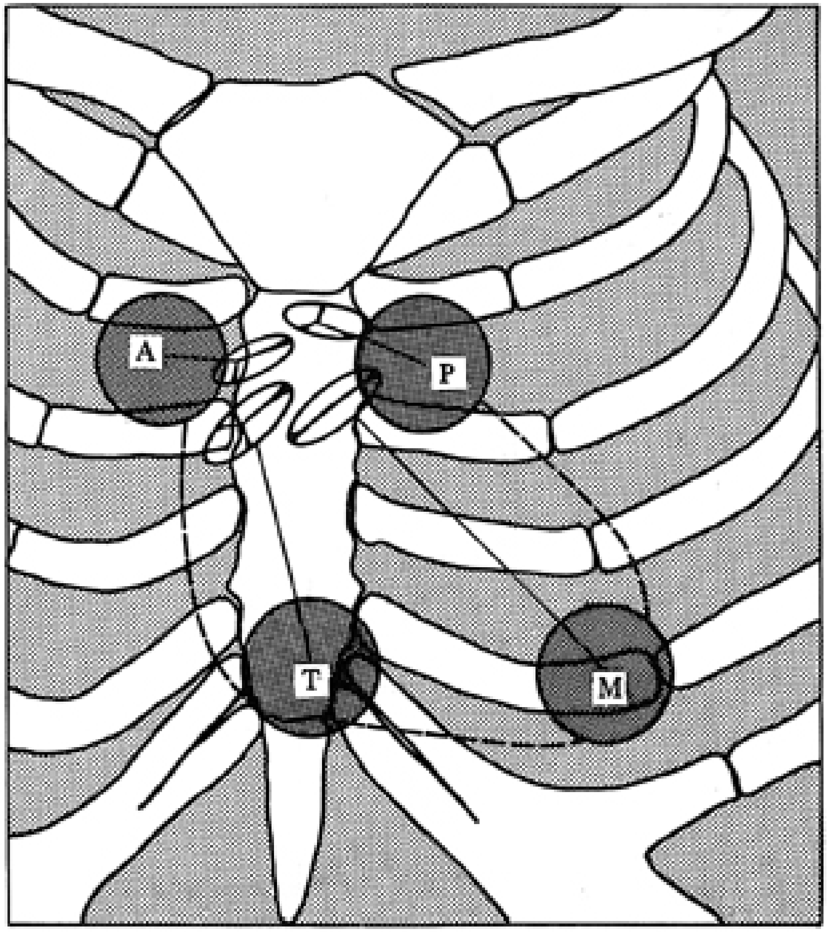
3rd: end ventricular filling

4th: contraction of atria and propelling blood into ventricles

Normal/Abnormalities

- Normal murmurs during early systolic phase in children.
- Abnormal ones due to stenoses and leaks at different valves (aortic, mitral, pulmonary).
- Measurement of time duration between murmurs, relation to heart cycle may determine the abnormality in the heart

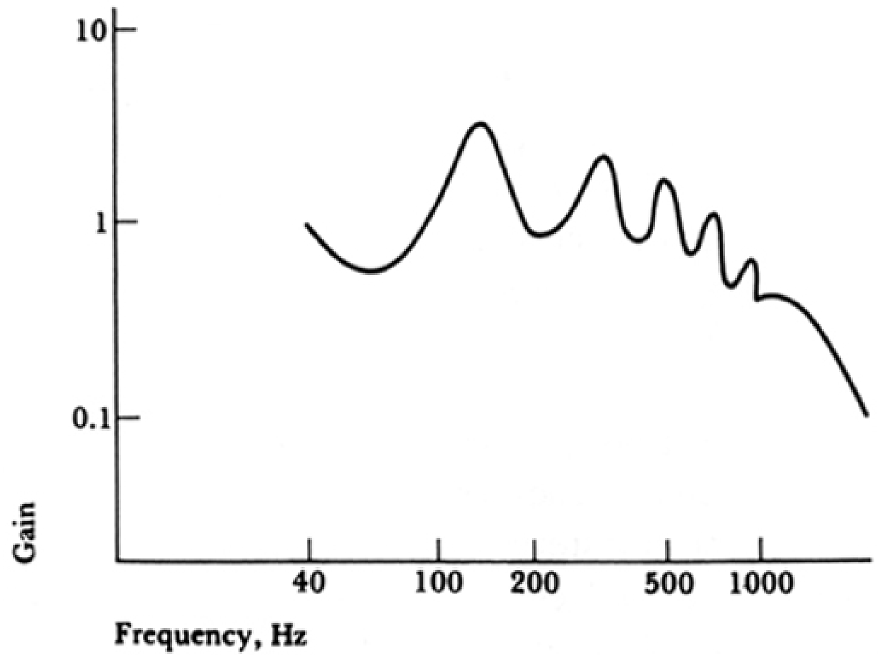
Auscultation techniques to measure heart sound



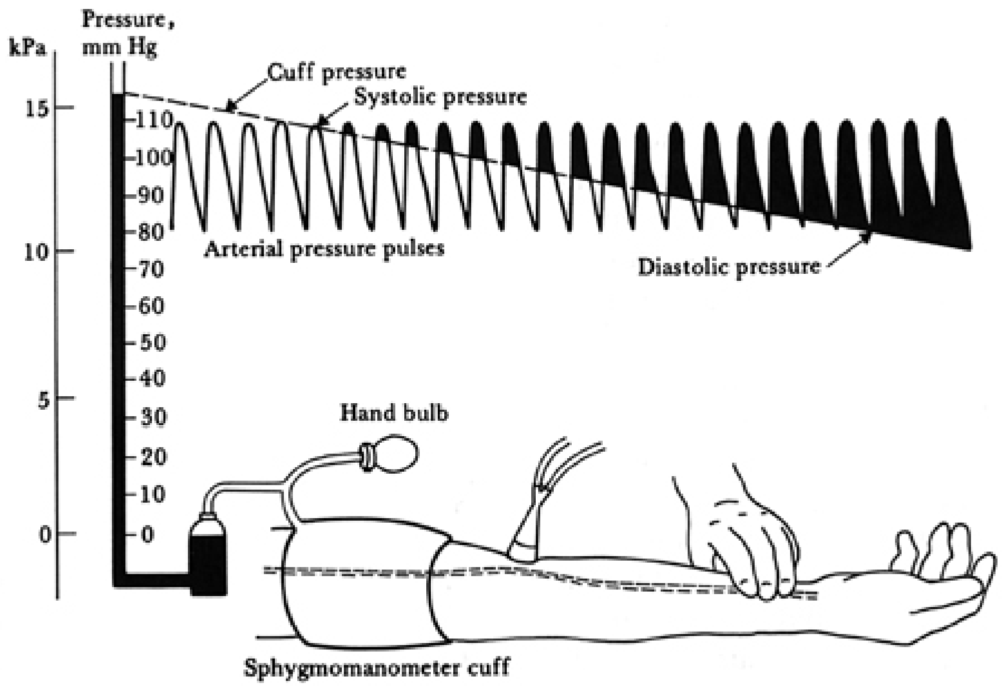
- BW of heart sounds (0.1-2000 Hz)

Stethoscopes

- Transfer heart sound through tube to ears
- Electronic stethoscopes (microphones), not accepted by many doctors since sound is different



Indirect measurements of BP Sphygmomanometer

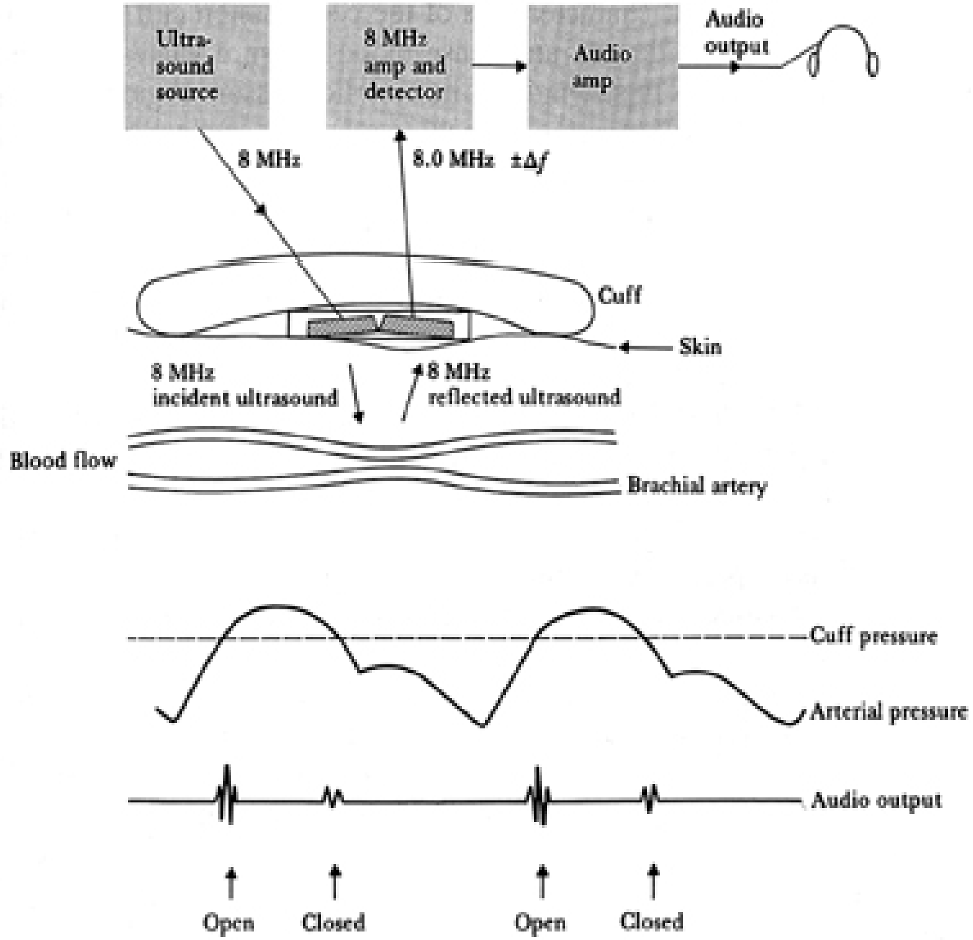


- Non-invasive
- Reduce cuff pressure ➔ blood flows➔ hear the sound in the scope
- Korotkoff sounds (20-300 Hz) are heart with a stethoscope
- Manometer reading at first sound is systolic pressure
- Sounds stop at diastolic pressure (why?)
- Automatic systems are also available.
- Less accurate for infants and hypertensive patients
- Not effective in noisy area

Automatic Detection of pressure

- Automatically inflate the cuff with known pressure
- Replace stethoscope with a microphone
- When the first Kortkoff sound detected, record pressure inside the cuff
- When sounds are no longer present, record cuff pressure,

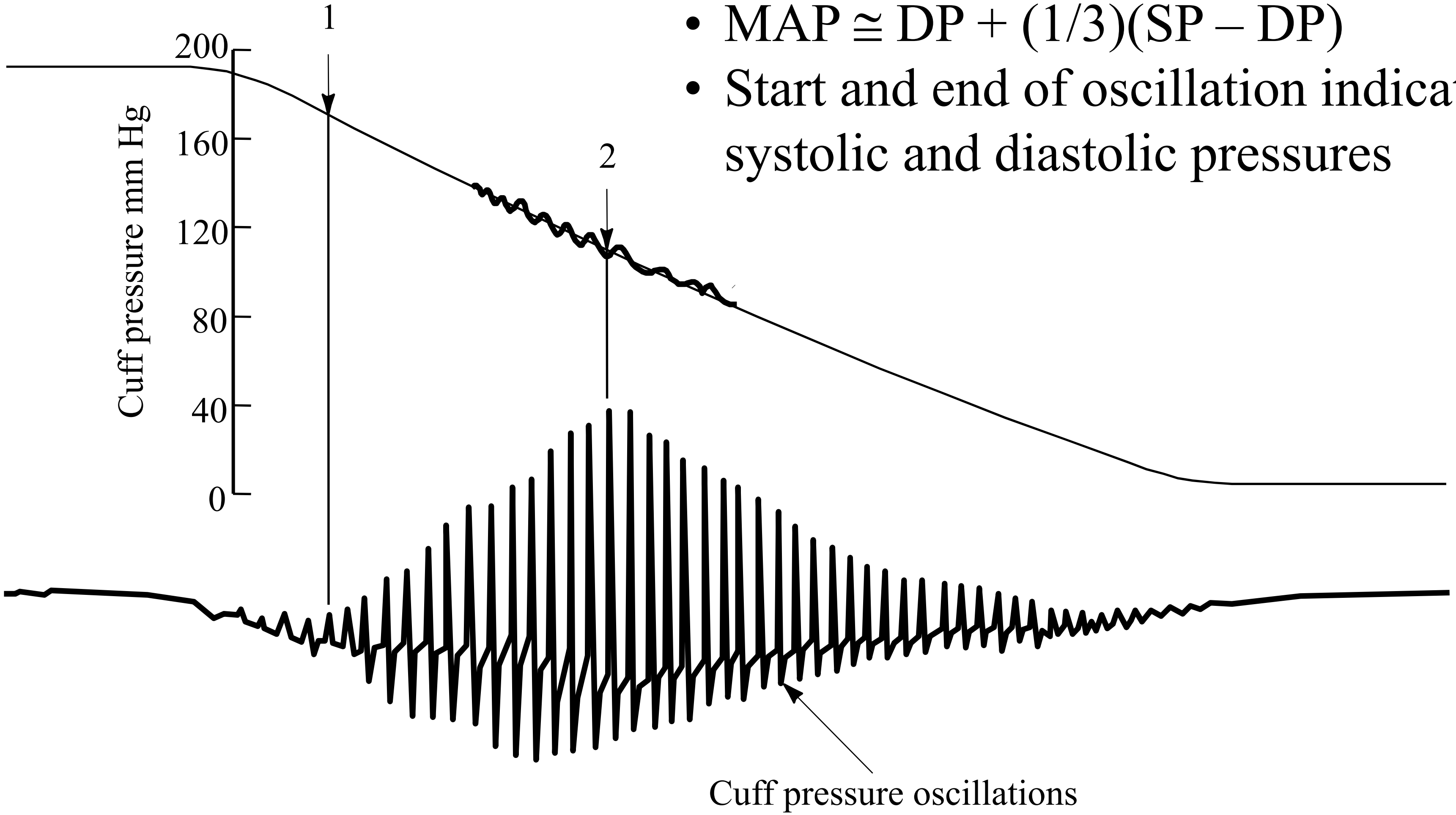
Ultrasonic determination of BP



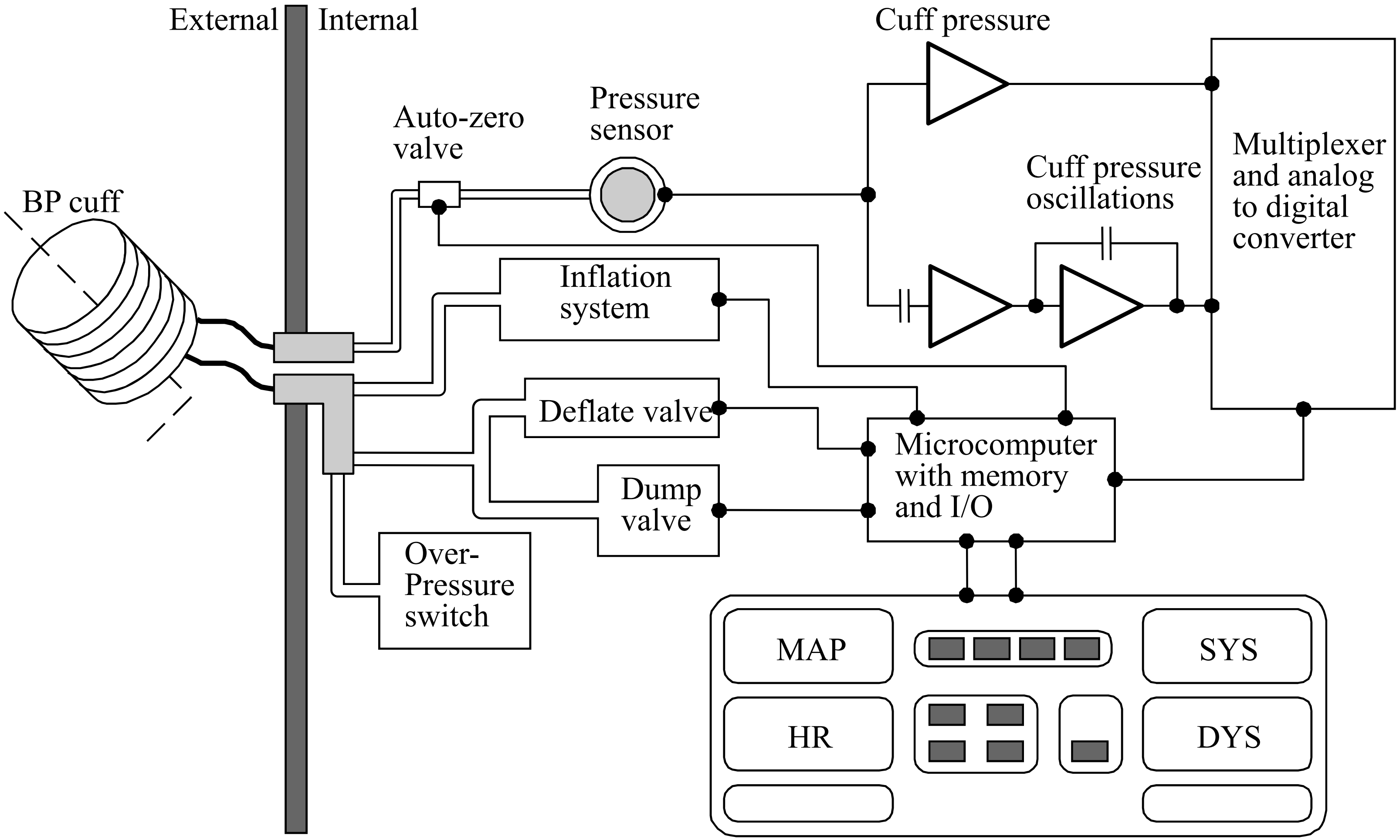
- Doppler sensor detect vessel wall motion.
- Inflate cuff with known pressure
- Start deflating, when motion is detected, record pressure
- When motion no longer detected, record pressure
- Good for infants and hypertensive patients

Oscillometric

- MAP ≅ DP + (1/3)(SP – DP)
- Start and end of oscillation indicates systolic and diastolic pressures



Block diagram of oscillometric type



References

- Webster (Medical Instrumentation)
- Dr Baha and Dr Haitham's class notes
- www.Wikipedia.com
- www.Cvphysiology.com