Measurement of flow and Blood Volume

Measurement of Blood Flow

- Turbines used in industrial applications for flow measurements can not be used due to:
  - Damage to blood cells;
  - Blood clotting
- Methods used for blood flow measurements
  - Indicator (dye or thermal) intensity
  - Electromagnetic induction
  - Ultrasonic transmission and reflection
  - Thermal convection
  - Radiographic principles
- Magnetic and ultrasonic blood flow meters measure velocity in exposed vessel during surgery.

Background info

- Flow verses concentration
  - If m_o amount of substance (indicator) is added into volume V; the concentration C is given by $C = m_o/V$;
  - As additional material m of the indicator is added, the change in the concentration is: $\Delta C = m/V$
  - If fixed quantity of indicator per unit time is added

$$\Delta C = \frac{dm/dt}{dV/dt}$$

- Therefore flow F in *l/min* is $$F = \frac{dV}{dt} = \frac{dm/dt}{\Delta C} \frac{(mg/\min)}{(mg/l)} \quad (1)$$

Indicator Intensity for Blood Flow Measurement

- Two approaches are used as the
  - Continuous infusion;
  - Rapid injection – bolus.
- Both only measure averaged flow over a number of heartbeats and do not pulsatile instantaneous flow

Continuous Infusion to measure blood flow

- Substance continuously added into the circulation, averaged over several heart beats.
  - Fick Technique (O_2 is used as indicator)
  - Thermodilution (heat is used as indicator)
- Measures averaged flow over a number of heartbeats
- Does not provide instantaneous flow values

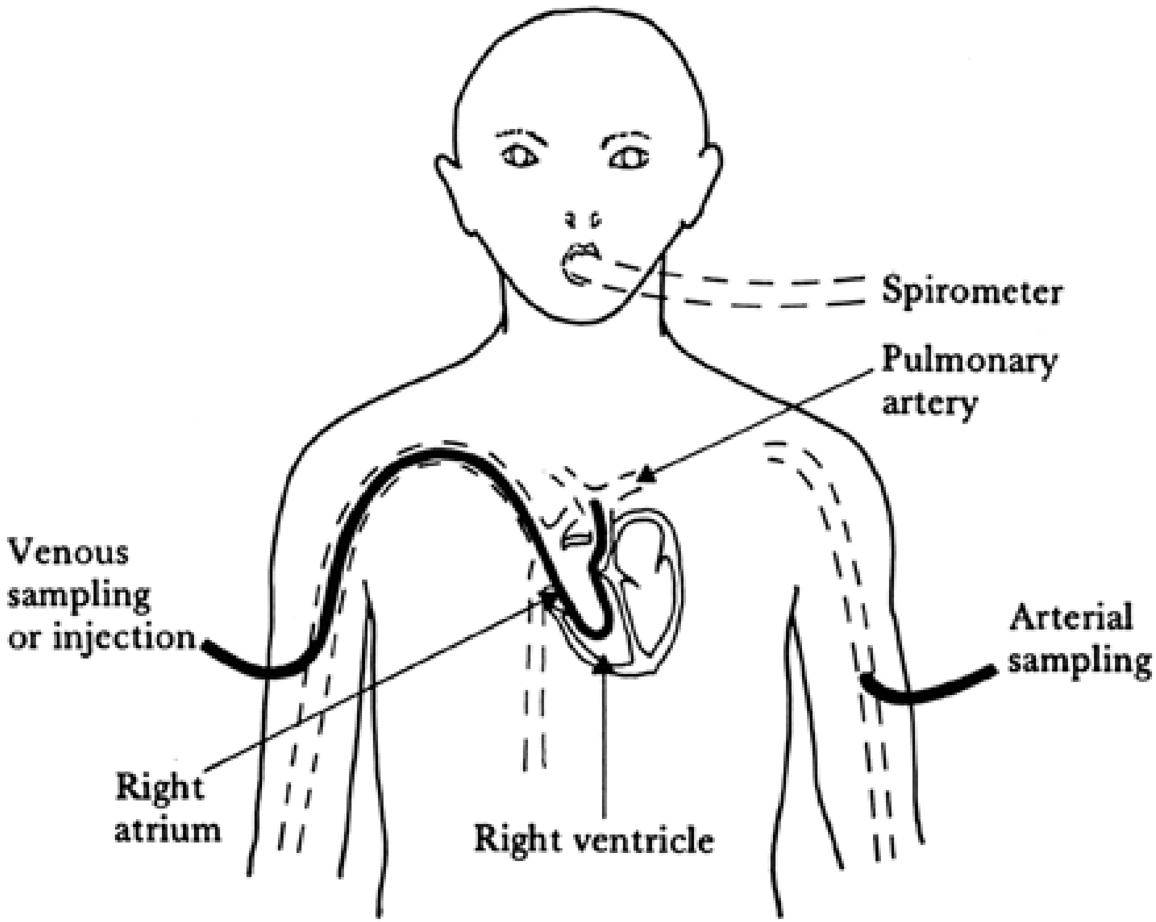
Cardiac Output Measurement (Fick Technique)

- Fick Technique uses O_2 as an indicator in the equation (1) to calculate the Cardiac output:

$$F = \frac{dm/dt}{Ca - Cv}$$

- F=Blood flow from the heart (cardiac output=stroke volume x heart rate)
- dm/dt= O_2 intake from the nose measured by a spirometer
- Ca= Arterial oxygen concentration found from samples taken from arm or leg artery.
- Cv=The venous oxygen concentration found from samples taken using a catheter placed into the pulmonary artery.

Fick Technique



Blood Flow Measurements

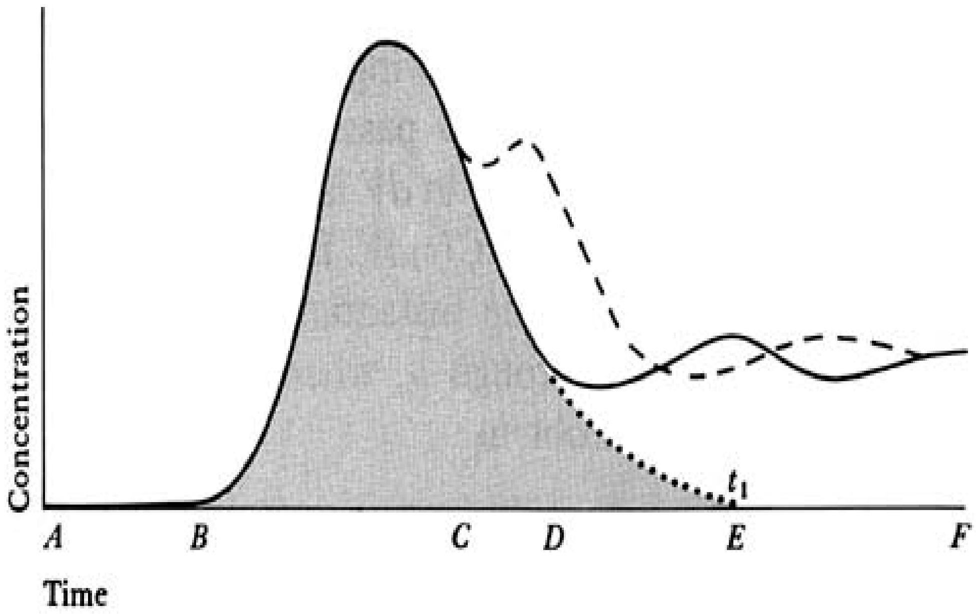
Indicator-dilution (intensity) method

- Measures averaged flow over a number of heartbeats
- Does not provide instantaneous flow values
- Continuous infusion
  - Substance continuously added into the circulation, averaged over several heart beats.
  - Fick Technique (O_2 is used as indicator)
- Rapid Injection of a dye solution
  - A known quantity of an indicator is rapidly injected into a vessel
  - Concentrations are measured downstream with time
  - The flow can be determined from the waveform of the concentration

Dye Dilution

- Dye must have following properties:
  - Motionless,
  - Harmless
  - Measurable
  - Economical
  - Always intravascular.
- Colored dye, **cardiogreen** is used. Optical detection of its concentration is possible. Its absorption peak is at around 805 nm, the wavelength at which blood optical absorption is independent of oxygenation.
- Blood oximeter measures the dye concentration.

Blood flow measurement using Dye Dilution



- Bolus injected at time A,
- Detect concentration change at time B, concentration increases till peak,
- Concentration decays to zero if no re-circulation.
- Waveform of concentration against time is obtained via a catheter drawing blood from the femoral or brachial artery

Blood flow measurement using Dye Dilution

- As discussed before the change in concentration of Dye is

$$\Delta C = \frac{dm/dt}{dV/dt}$$

$$\frac{dm}{dt} = C(t) * \frac{dV}{dt}$$

$dm = F*C(t)\, dt$ yielding $m = \int_0^t FC(t)dt$

Average flow $F = \dfrac{m}{\int_0^{t_1} C(t)dt}$

Thermodilution

- Temperature = concentration of heat per unit volume
- Bolus of cold saline is injected to the blood stream at the right ventricle and measurement of temperature is made by a thermistor at the pulmonary artery

$$F = \frac{Q}{\rho_b c_b \int_0^{t_1} \Delta T_b(t)\,dt} \left(m^3/s\right)$$

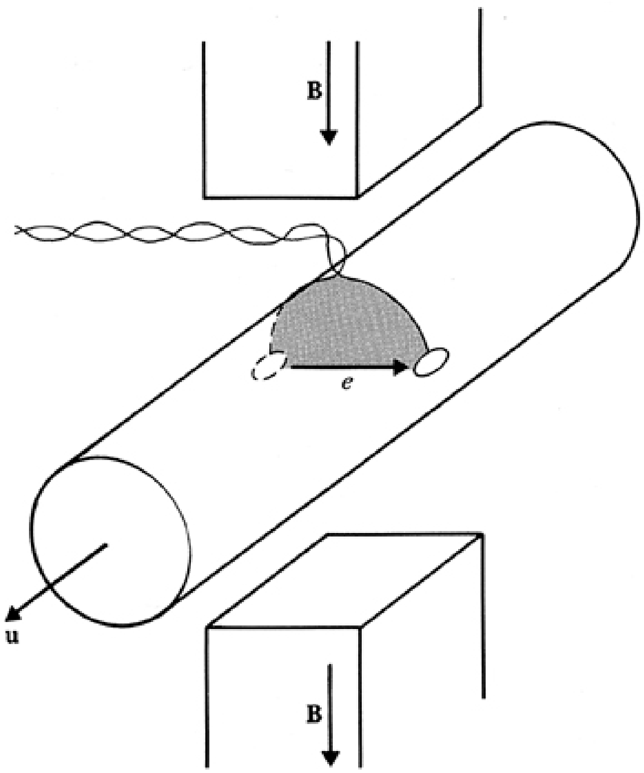
where

Q : the heat content of the injectate, J (=ViΔTiρici),

ρb : density of blood (kg/m3)

cb : the specific heat of blood J/(kg.K)

Electromagnetic flowmeters

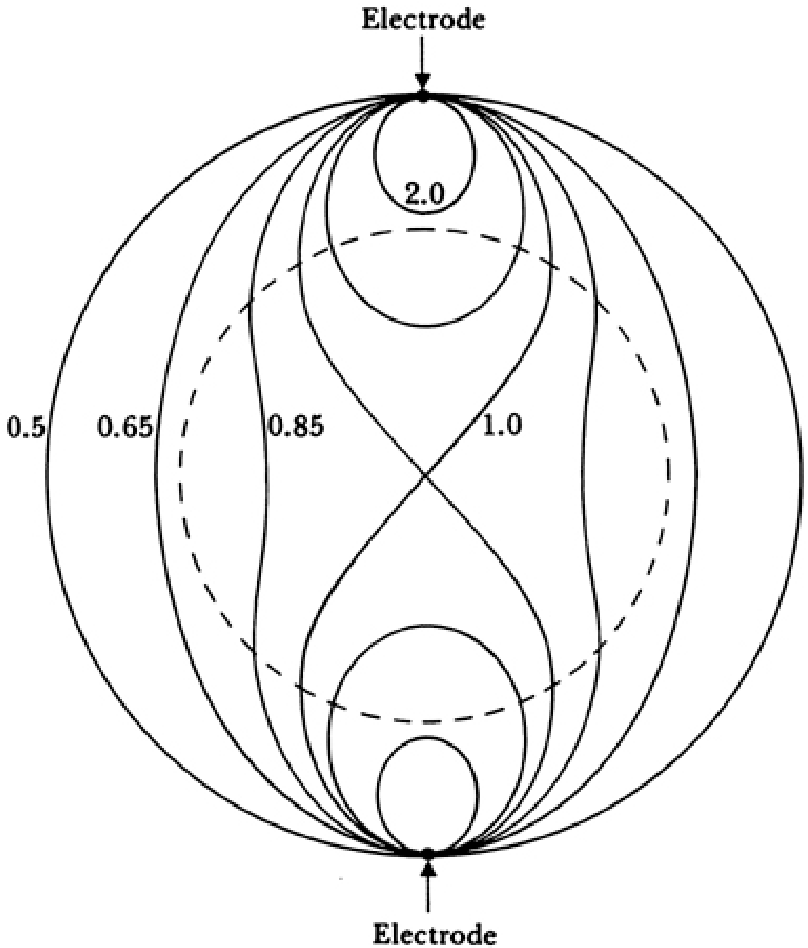


- Measure instantaneous pulsatile flow
- Faraday's law (moving inductance in a magnetic field produces induced emf (current)).

$$e = \int_0^{L_1} \vec{u} \times \vec{B} \bullet d\vec{L}$$

- B: flux density
- u : velocity
- L: Electrode length
- For uniform B and u, $e = Blu$
- Expose blood vessel in surgery and place electrodes on sides of artery together with magnetic field

Errors with the Electromagnetic flowmeters



- Regions with high velocities generate higher emf's➔ variable resistance
- Wall of vessel causes error
- Body fluids have higher conductivity than the blood, they may shunt (short) the emf
- Magnetic flux density is not uniform in horizontal or axial planes

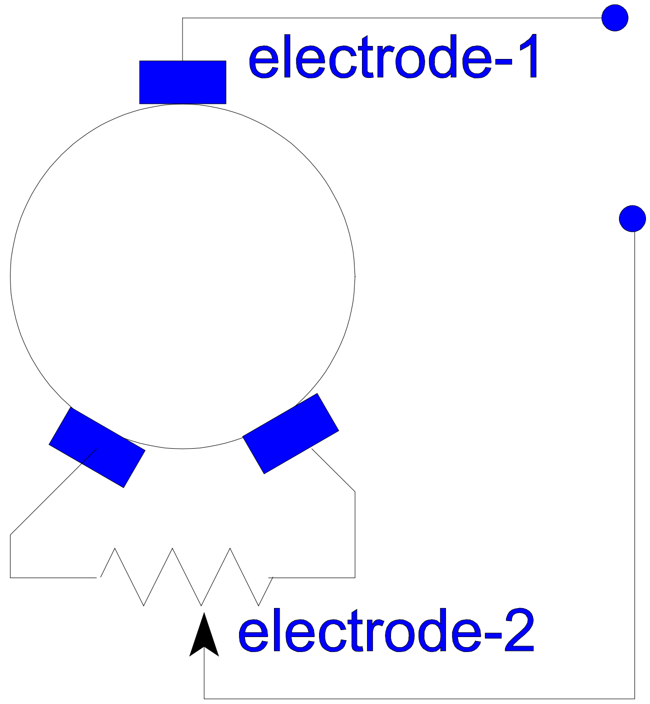
DC flowmeters

- Use DC magnetic field
- Were not satisfactory due to
  - Electrode-electrolyte potential at the same order as the induce voltage due to the flow➔ emf can't be detected
  - The ECG has similar frequency components and it has larger signal (near the heart)
  - 1/f noise is large which yield poor SNR
- Use AC magnetic field

AC flowmeters

- AC magnet current (400 Hz)
- Problem of the transformer voltage
  - Higher than the flow voltage and proportional to dB/dt
- Solutions
  - Phantom electrode
  - Sampling
  - Quadrature suppression
  - Square-wave excitation

Phantom electrode



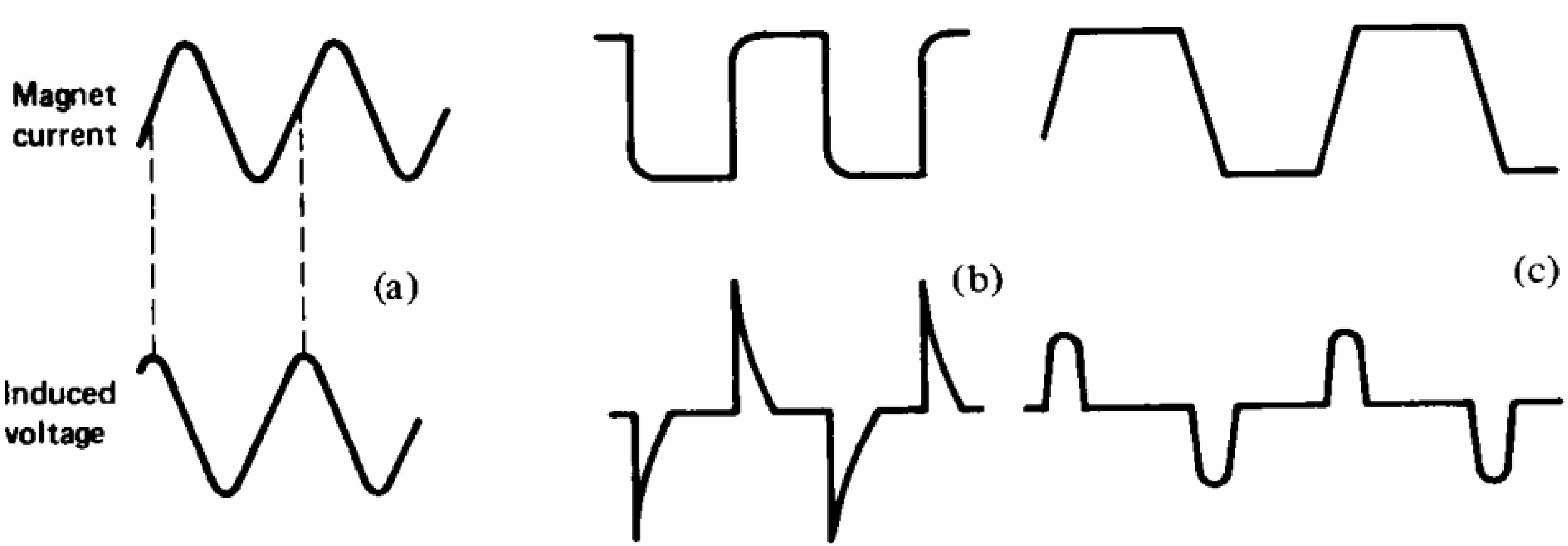
The variable resistance adjusts the direction of the field till it is parallel to the external field

Square-wave excitation

Sine wave excitation

Square wave excitation

Trapezoidal wave excitation



Transformer voltage

Peaks may saturate the amplifier

Mostly used type of excitation

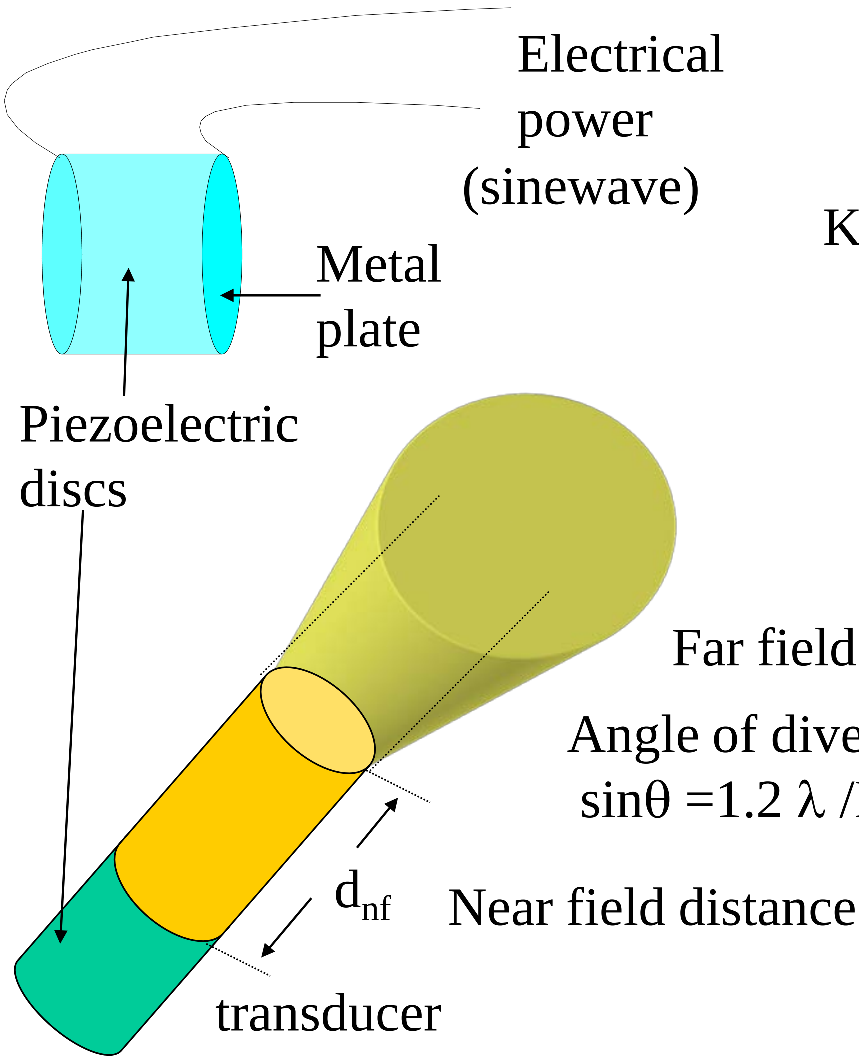
Ultrasonic flowmeter

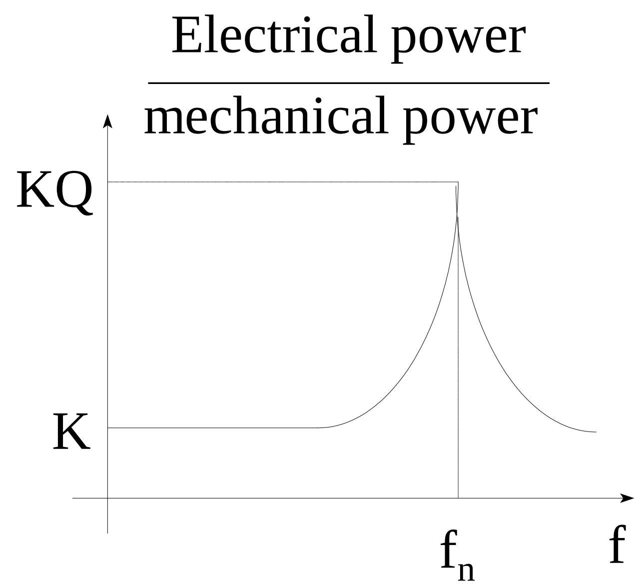
- Measures instantaneous flow.
- Can be beamed through the skin (non-invasive).
- Advanced types can measure flow profiles.
- Two basic methods:
  - transmission (transit-time)
  - reflection (Doppler); 1st continuous wave, 2nd pulsed

Material and Arrangements

- It is a piezoelectric material that converts electrical power to acoustic form and vice versa.
- Lead-zirconate titanate has highest conversion efficiency. It introduces piston-like pressure waves into the tissue.
- Propagation velocity over the transmission frequency yields the wavelength. For maximum efficiency crystal must be $\lambda/2$ thick.

Piezoelectric Crystal





Angle of divergence in far field:
$\sin\theta = 1.2\,\lambda / D$

Near field distance $d_{nf} = D^2/4\lambda$

Piezoelectric Crystal

To have near field extending to longer distances, use higher frequencies and larger transducers. The near field length

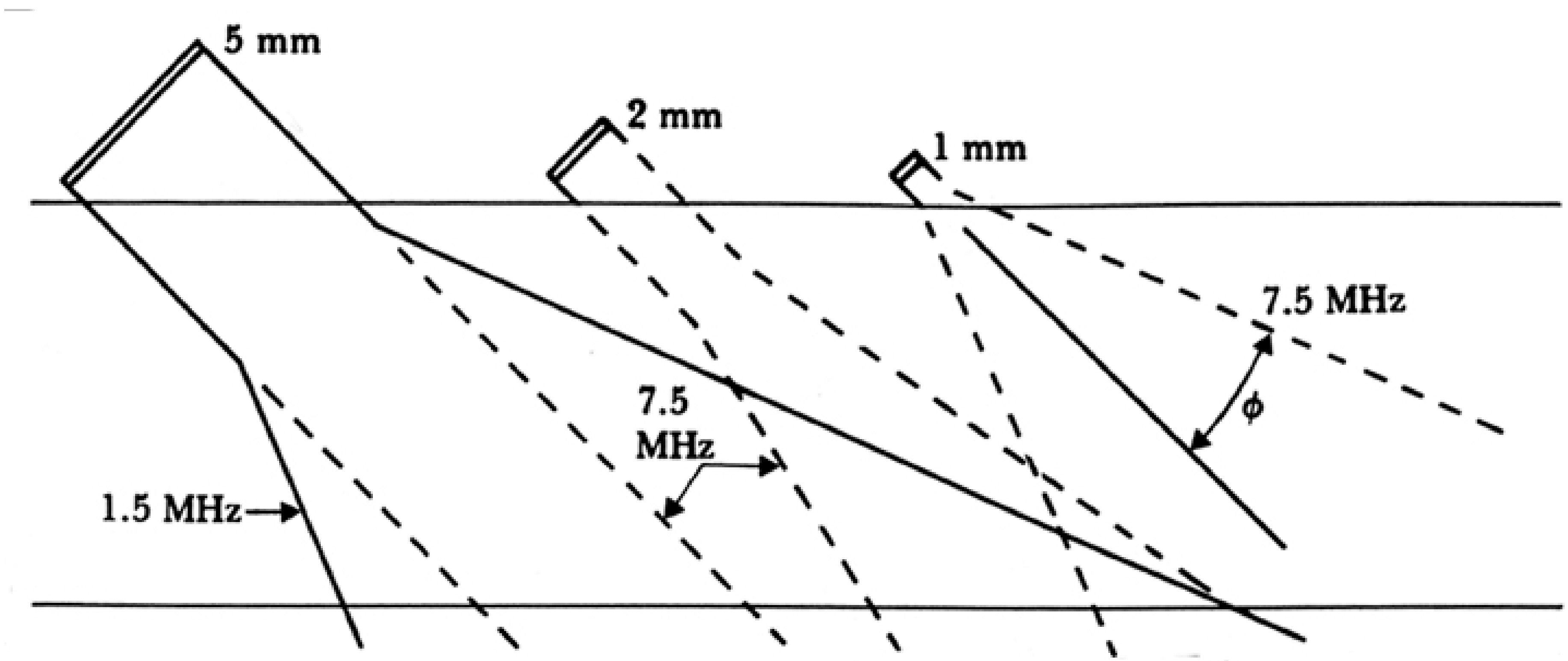
$$d_{nf} = \frac{D^2}{4\lambda}$$

where D is the diameter of the transducer and λ is the wavelength. The angle of divergence in the far field can be found as:

$$\sin\theta = \frac{1.2\lambda}{D}$$

Near and far fields for various transducer diameters and frequencies

The solid line for 1.5 MHz, and dashed line is for 7.5 MHz

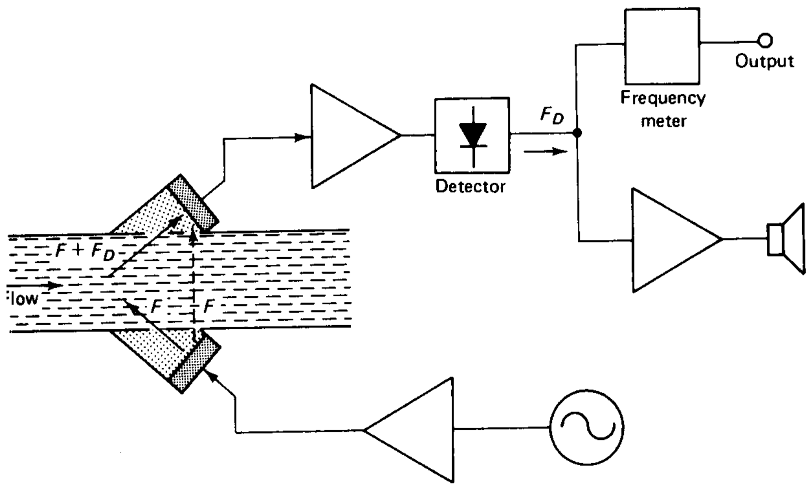


Selection of Frequency

- Power decays exponentially due to absorption of heat in the tissue that is proportional to frequency f. This indicates use low frequencies.
- In many applications we use back-scattering whose intensity is proportional to f^4. This indicates use of high frequencies.
- As a compromise, frequencies in the range 2 to 10 MHz are used

Ultrasonic Blood Flowmeter, Doppler Type

- Doppler effect states that the frequency of a wave reflected off a an object moving away from the source is lower than the frequency of the source signal.
- In the Doppler (Reflection) technique two methods are used as: continuous wave and pulsed
- Reflection depends on the existence of cells in the blood.
- Reflection is due to change in acoustical impedance. Reflected beam moves in all directions.



Doppler Frequency

Doppler frequency is calculated according to: $f_d / f_o = u / c$, where

f_d = Doppler frequency shift

f_o = source frequency

u = target velocity

c = velocity of the sound

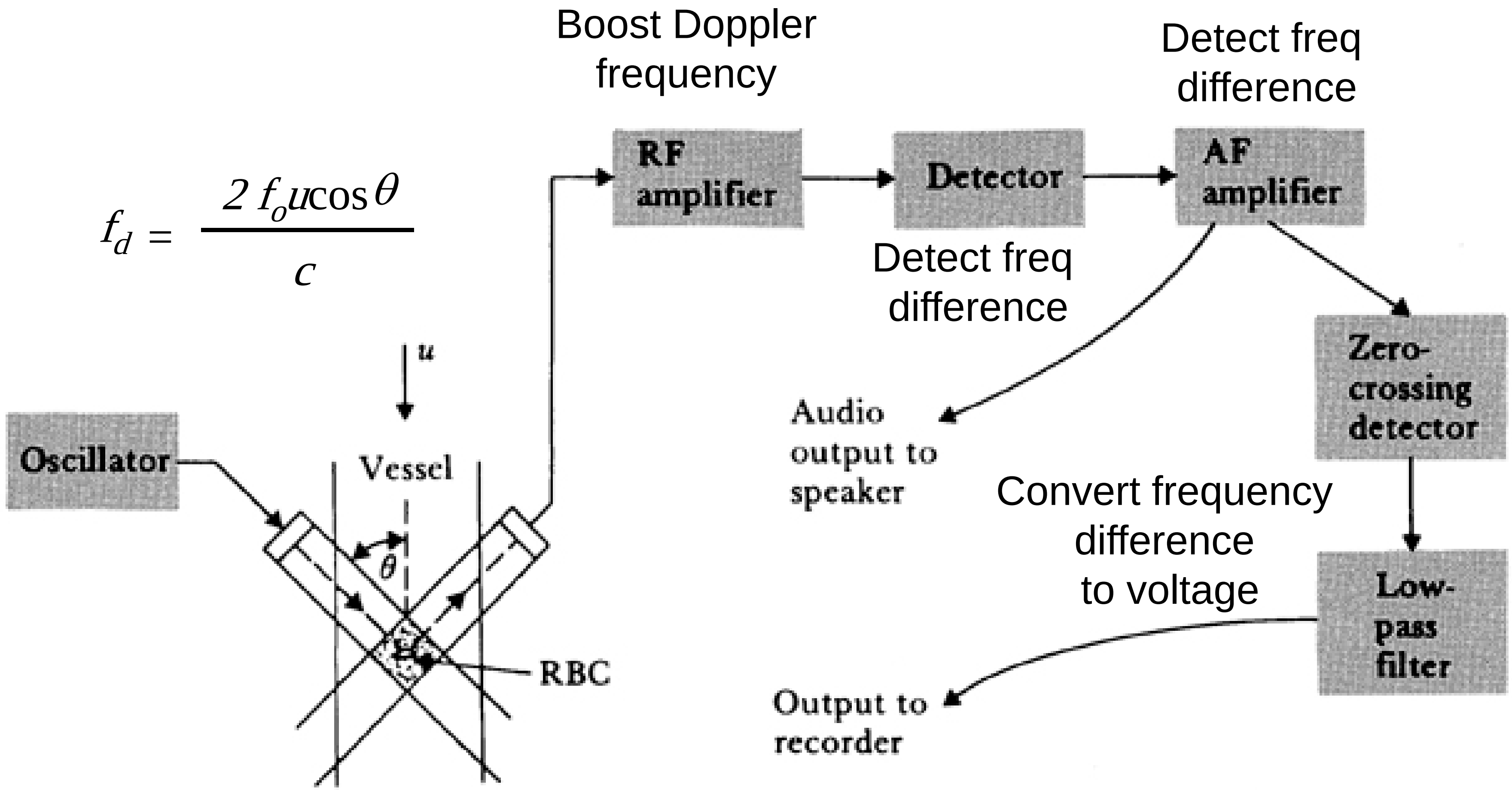
Two shifts due to two paths yielding $$\frac{f_d}{f_0} = \frac{2u}{c+u} \cong \frac{2u}{c}$$

The approximation is valid since c ≅ 1500 m/s and u ≅ 1.5 m/s. We have to take the transmission angle θ into consideration. Then the Doppler frequency becomes

$$f_d = \frac{2 f_0 u \cos\theta}{c}$$

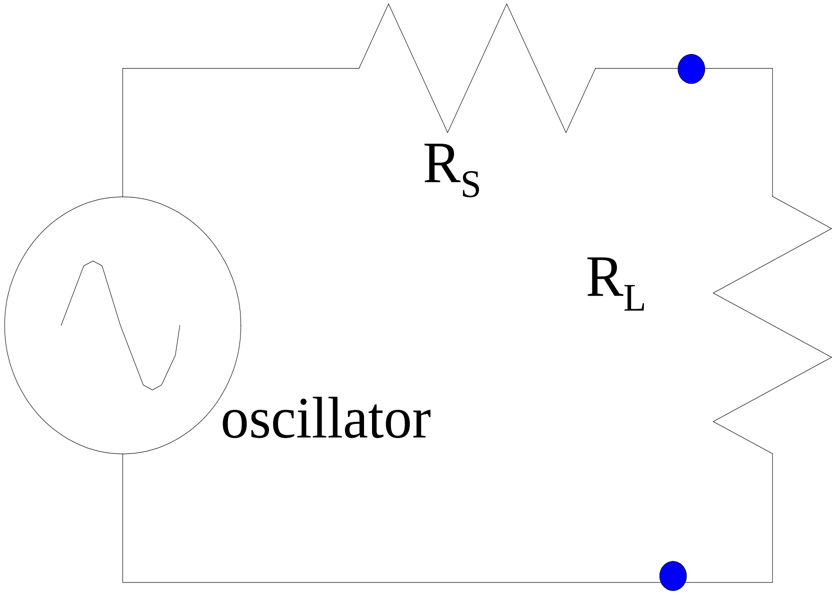
Principle Circuits

$$f_d = \frac{2 f_o u \cos\theta}{c}$$

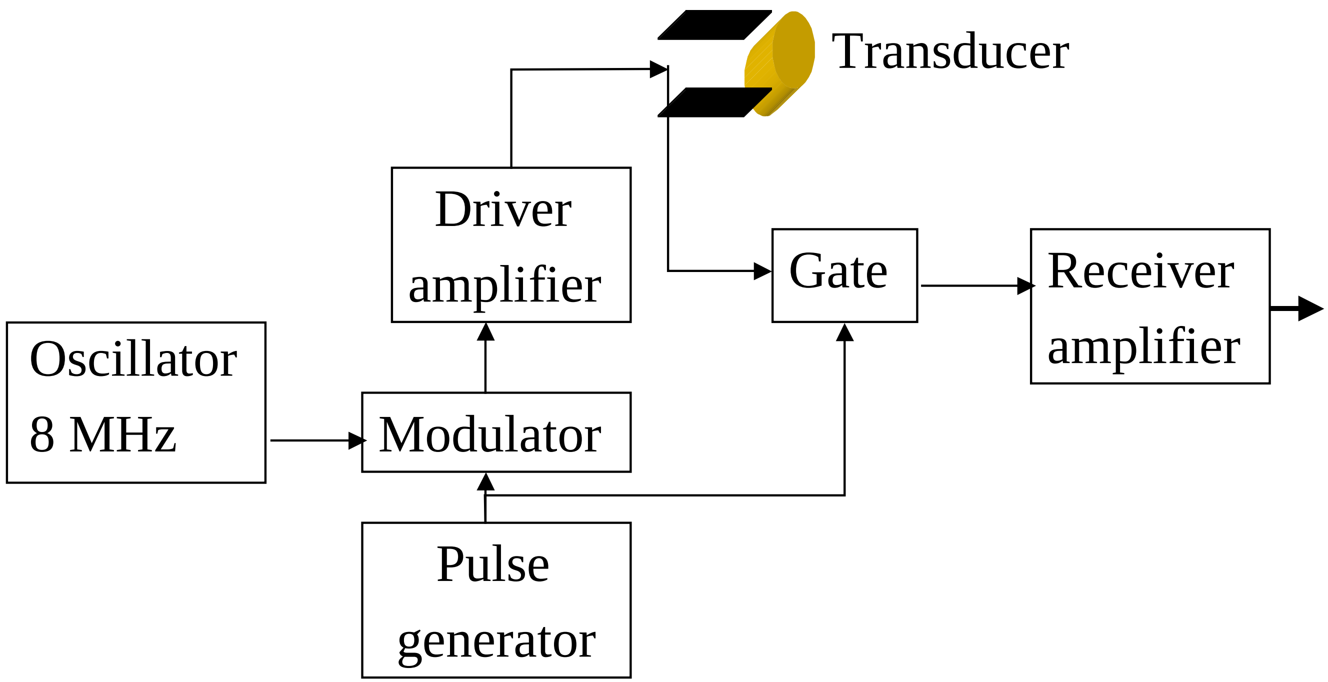


Impedance Requirement

- Crystal operating at resonance has an input impedance about 100 Ω and $R_L = R_S$ is needed for the maximum power transfer.
- Low output impedance at the oscillator is needed to drive the crystal



Pulsed Doppler



Pulse Repetition Frequency

Two important factors must be considered in selecting the pulse repetition frequency.

A. Range ambiguities: return from first pulse must be analyzed before sending the next. Therefore, $f_r < c/(2R_m)$ where R_m = maximal useful range.

B. Sampling theorem: $f_r > 2f_d$

Combining the two:

$$f_d = \frac{f_0 2u \cos\theta}{c} \prec \tfrac{1}{2} f_r \prec \frac{c}{4R_m}$$

that yields

$$R_m u_m \cos\theta \prec \frac{c^2}{8 f_0}$$

Problems

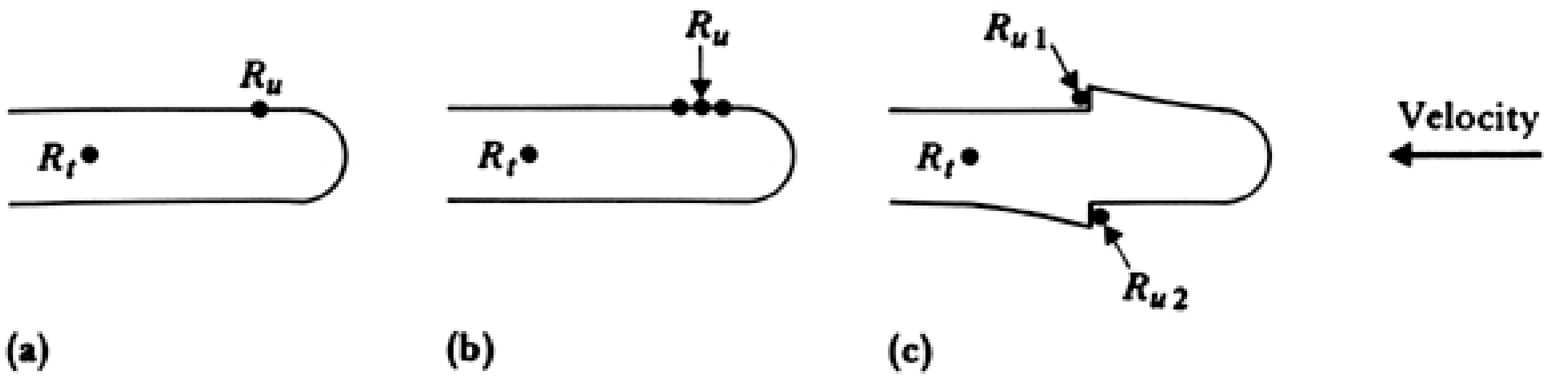
- Spectral spreading due to Multiplication of sine wave with a pulse
- Convolution of the input wave with the velocity profile
- Aliasing; it can be prevented by using higher sampling rate.
- Q of the transducers.
  - To reducing ringing Q is chosen between 3 and 5
  - Low Q reduces the transmission efficiency.
  - In practice Q between 5 and 15 is used.

Laser Doppler Blood Flowmeter

- 5-mW He-Ne laser beams 632.8 nm lights through fiber optics into the skin. Moving blood cells in skin frequency shifts the light and causes spectral broadening. Reflected light is carried by fiber optic to a photodiode.
- Filtering, squaring and dividing are necessary for signal processing.
- Capillary blood flow is studied

THERMAL VELOCITY SENSORS using heated thermistors

Principle: The flow lowers the temperature of a heated thermistor. The temperature reduction and velocity are non linearly related



Heat dissipated by the thermistor

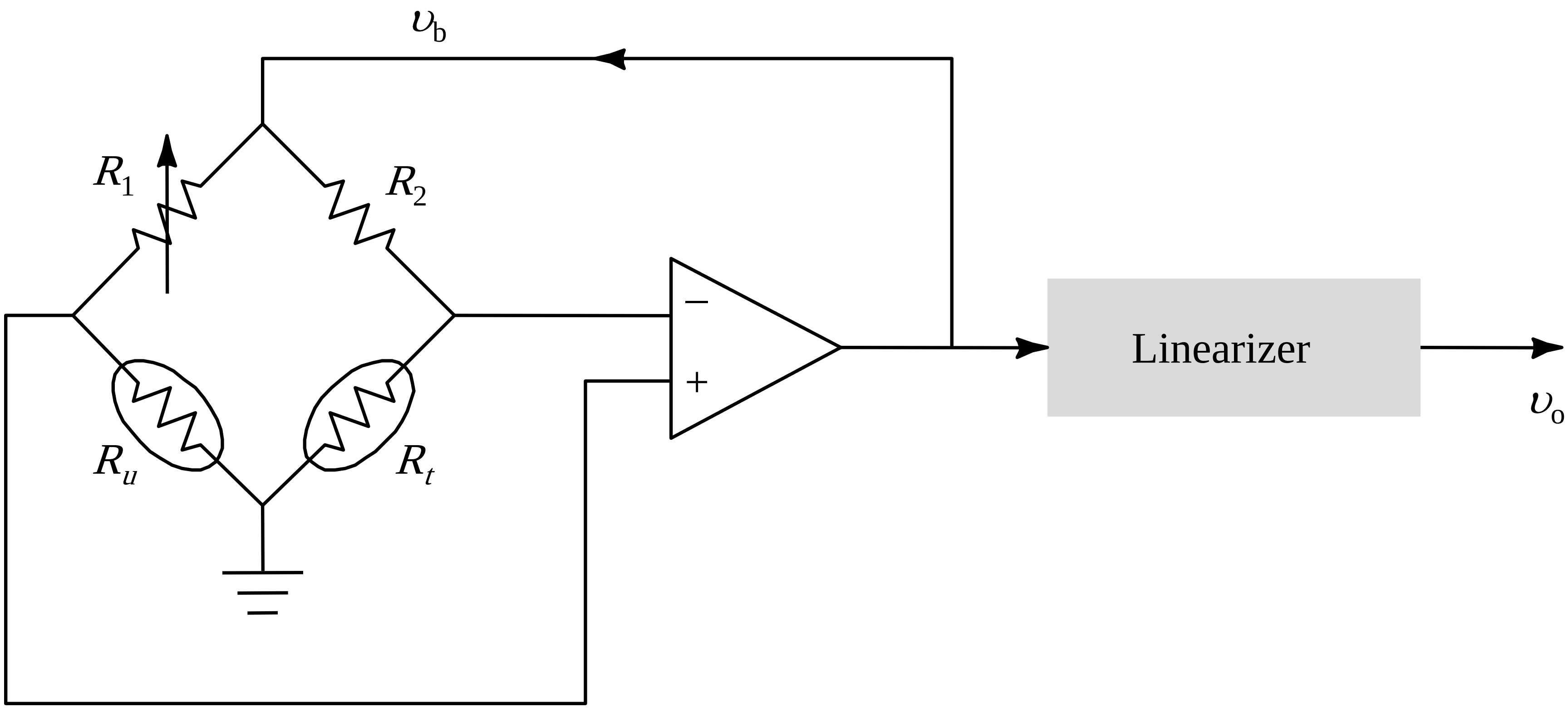
$$W/\Delta T = a + b\log u$$

velocity

Temperature difference

constants

Thermal velocity meter circuit



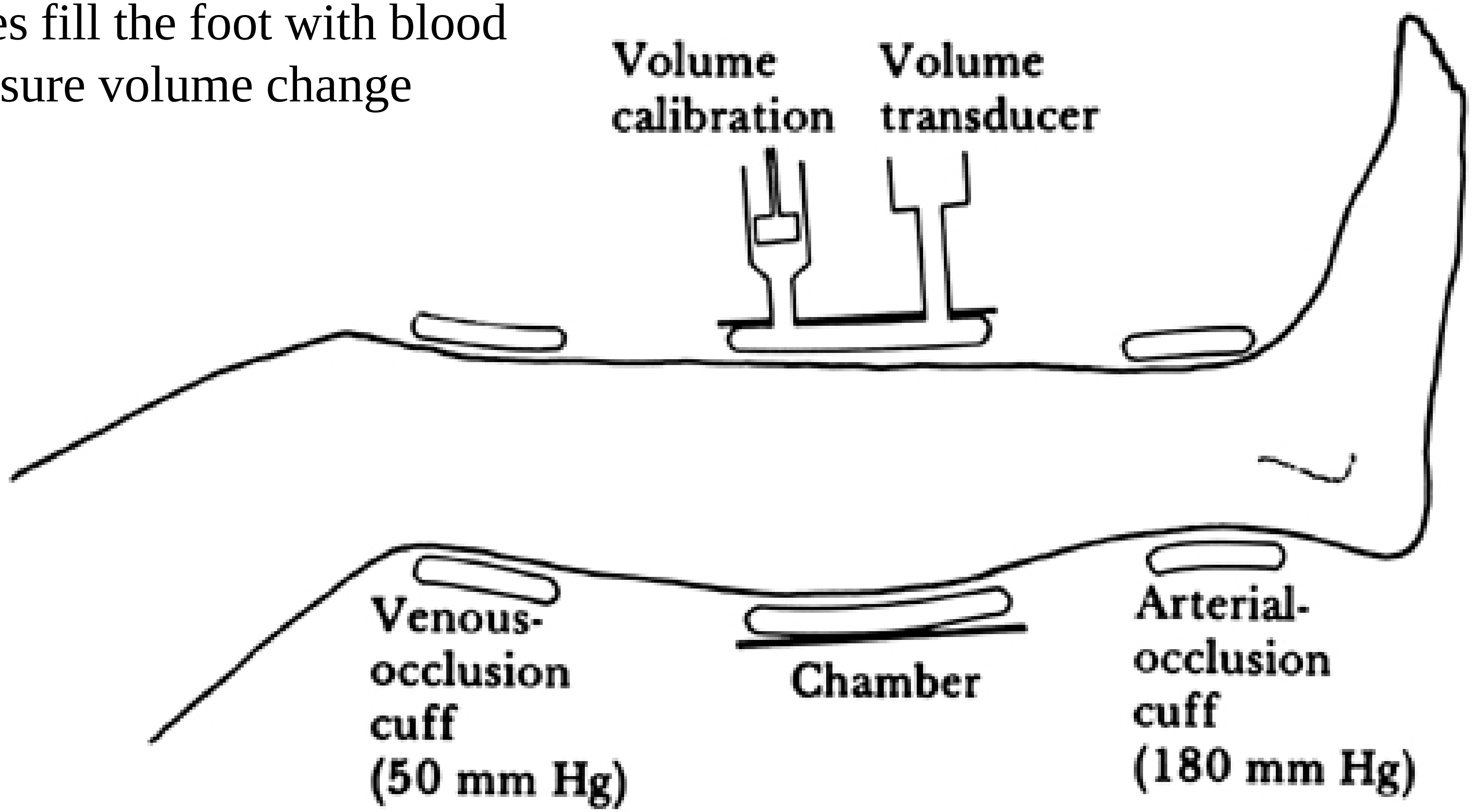
PLETHYSMOGRAPHY

A non-invasive technique to measure changes in volume; $F = dV/dt$

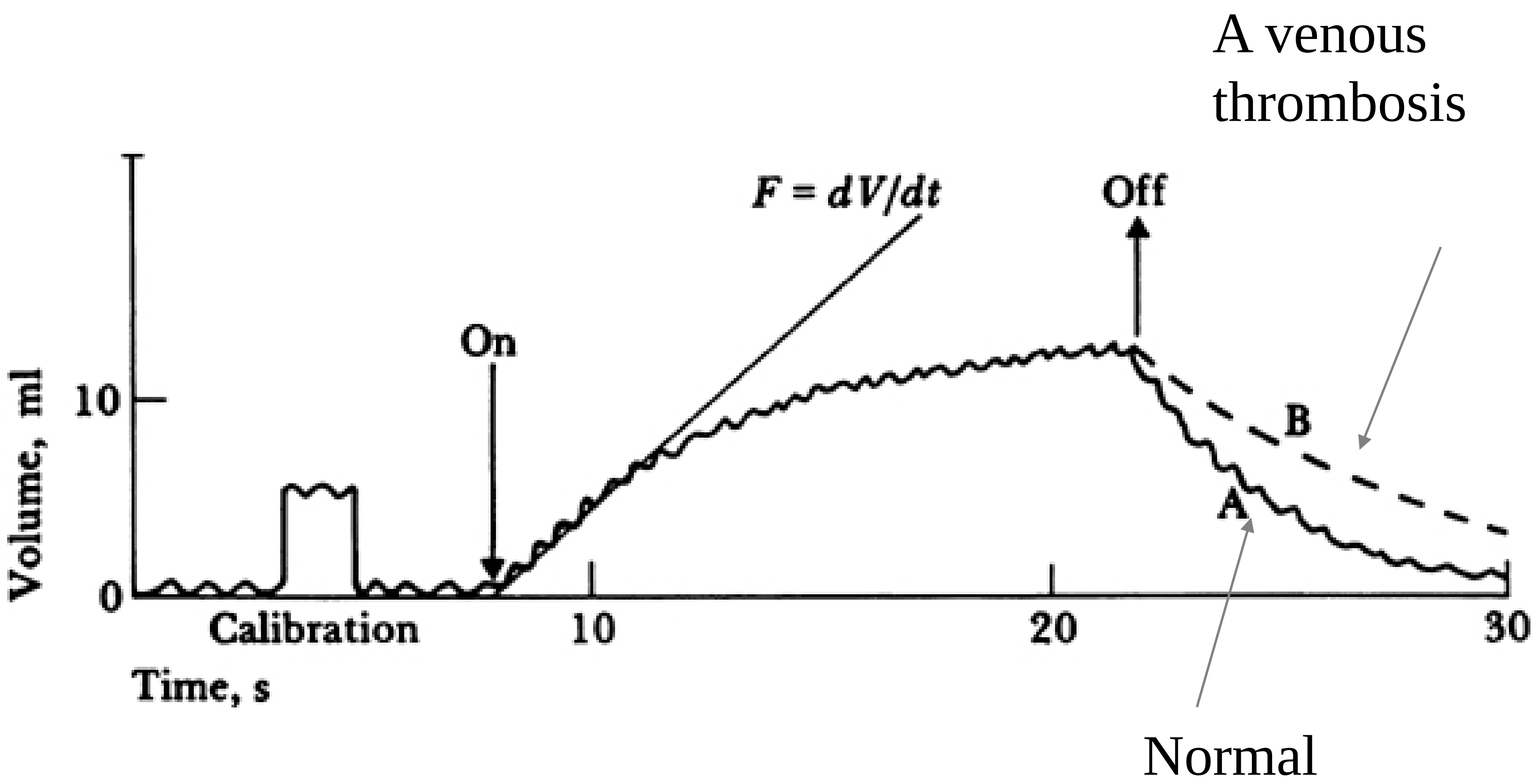
- True or direct (chamber) plethysmography
- Indirect plethysmography
  - electrical impedance plethysmography
  - photoplethysmography

Two-cuff chamber plethysmography

Principle: Stop venus blood,
let arteries fill the foot with blood
then measure volume change



Typical Waveform



Electrical Impedance Plethysmography

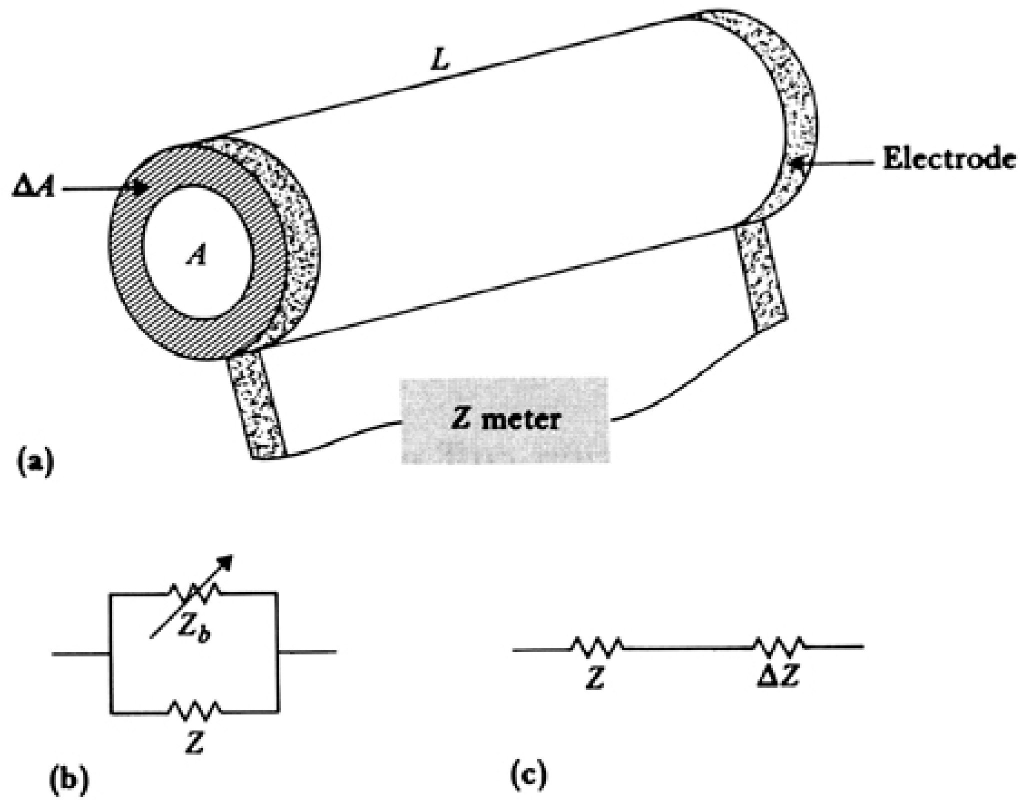
As the volume of the limb changes, its electrical impedance changes. Assumptions:

- 1. Expansion of arteries is uniform;
- 2. The resistivity of blood ρb is constant (ub $\uparrow \rightarrow \rho b \downarrow$)
- 3. Lines of current are parallel to the arteries

Electric Plethysmography

Principle:

- Block venous return
- Shaded area represents increase in A due to blood filling.
- The added blood is an impedance Z_b that is parallel to the original impedance of the leg
- An impedance meter usually measures ΔZ



A model for impedance pletysmography.

- A cylindrical limb has length L and cross-sectional area A. with each pulse A increases by the shaded area ΔA.
- This causes impedance of the blood, Z_b , to be added in parallel to Z.
- Usually ΔZ is measured instead of Z_b .

$$Z_b = \rho_b L / \Delta A; \Delta V = \Delta A L = \rho_b L^2 / Z_b$$

$$\Delta Z = [(Z_b // Z) - Z] = -Z^2 / (Z_b + Z)$$

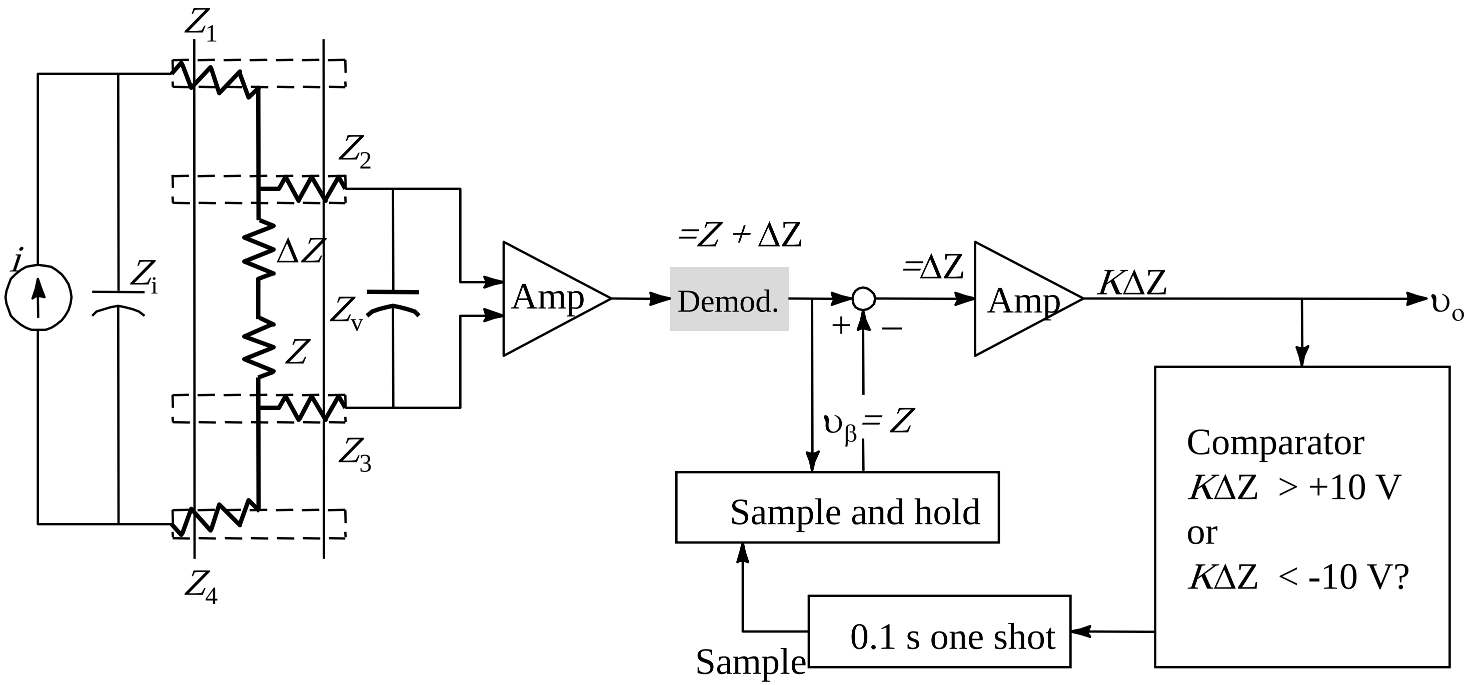
new old

With $Z \ll Z_b$, $1/Z_b \cong -\Delta Z/Z$ yielding $\Delta V = - \rho_b L^2 \Delta Z / Z^2$

How to measure the impedance?

- AC current at about 100 kHz is used. Why?
  - Electrode impedance drops drastically with f;
  - Electrical safety; we can apply high currents at high frequencies $\rightarrow$ signal to noise ratio (SNR)$\uparrow$
  - However, stray capacitances will be effective if frequency is too high.
- Use a constant amplitude AC current and measure the voltage

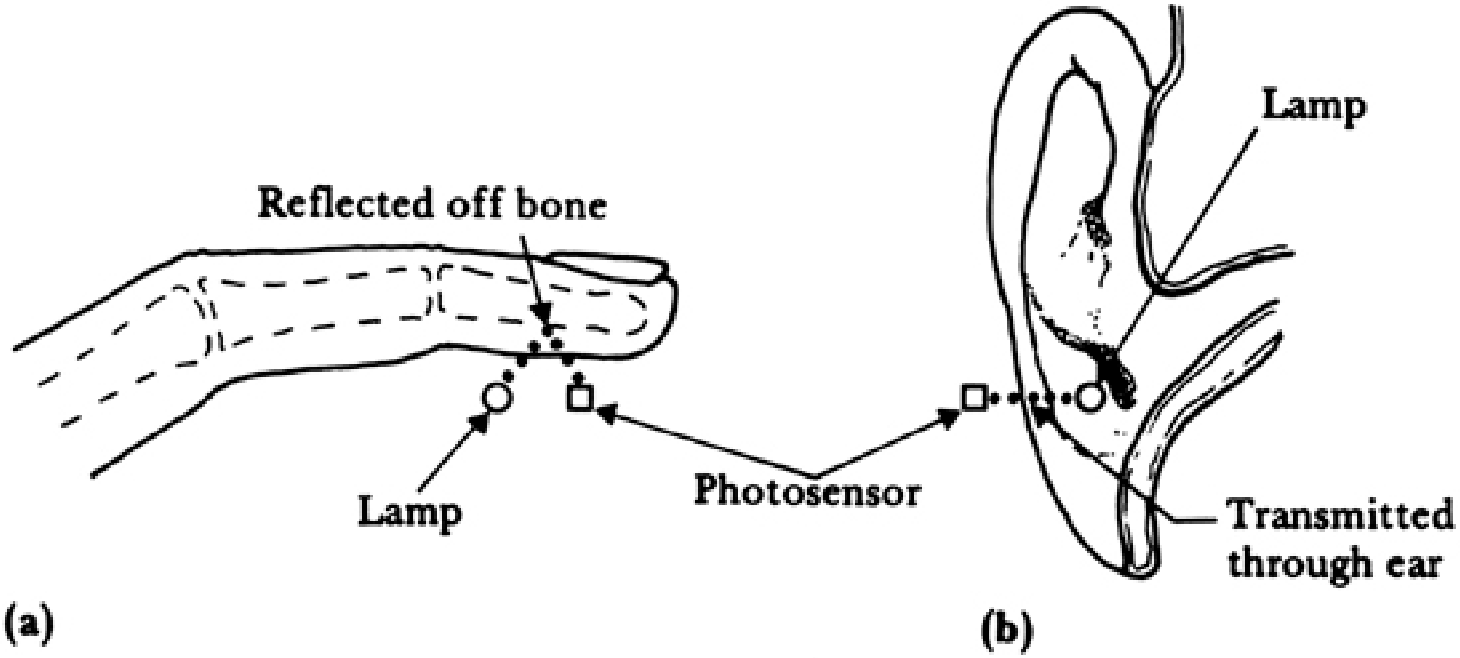
Four Electrode Plethysmography



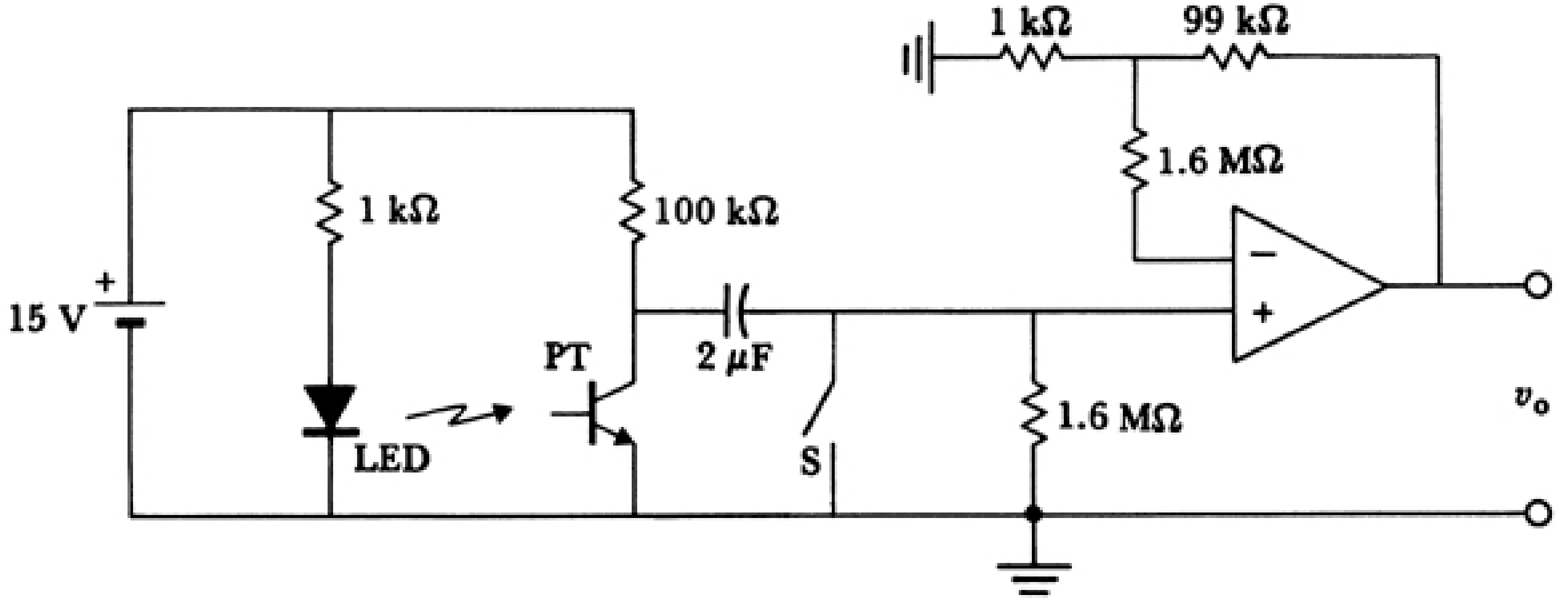
- Current is injected through two outer electrodes, and voltage is sensed between two inner electrodes.
- Ampl + demod = Z+ΔZ

Photoplethysmography

- Reflection, absorption and scattering of light depends on how much blood is flowing into the organ.
- Use LED with narrow band light and peak at 940 nm as the source
- Use a photo-resistor with a filter to restrict light from being detected



Simplified circuit



HW5

- Q 8.4, 8.7, 8.11, 8.14, 8.18