Universidad de Valparaíso
CHILE

(Photo) Plethysmography

Mediciones Biomédicas 2024

Ingeniería Civil Biomédica

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Plethysmography

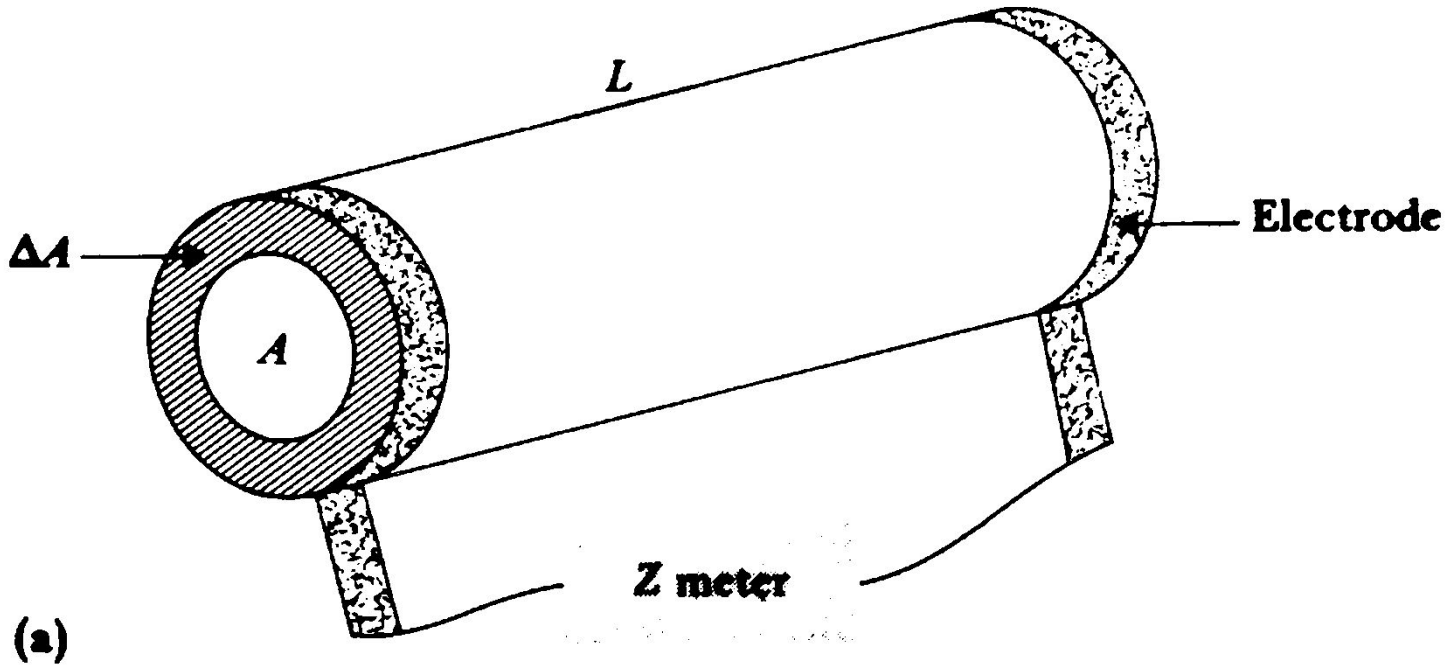
- Measurement of volume changes within an organ or whole body (usually resulting from fluctuations in the amount of blood or air it contains) or related phenomena is called *Plethysmography*

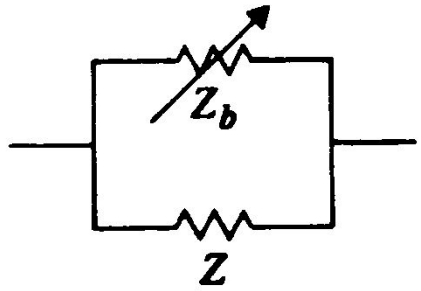
- Types:
    - Electrical Impedance Plethysmography
    - Chamber Plethysmography
    - Photo plethysmography

Impedance Plethysmography

- Electrodes are attached to a segment of tissue
- The resulting impedance is measured.
- As the volume of the tissue changes, in response to the pulsation of blood (as happens in a limb) or the resistivity changes in response to increased air in the tissue, the impedance of the tissue changes.

Impedance Plethysmography





Impedance Plethysmography

- The electrodes are either **conductive bands** wrapped around the limb or digit to be measured or simple **conductive strips or tape** attached to the skin.

- In either case, the electrodes contact the skin through a suitable electrolyte jelly or paste to form an electrode interface and to remove the effect of skin resistance.

Impedance Plethysmography

- With each pulse, the cross sectional area ***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
- The shunting impedance of the blood, Z_b, is due to the additional blood volume ***ΔV*** that causes the increase in cross-sectional area ***ΔA***

Impedance measurement

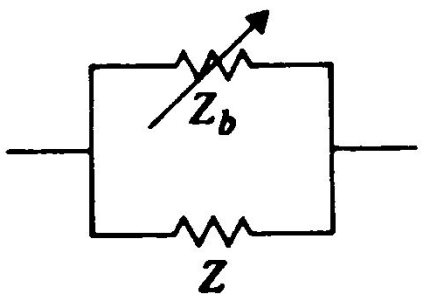
$$Z_b = \frac{\rho_b L}{\Delta A}$$

where

- ρ_b - Resistivity of the blood
- L - Length of the segment of tissue between the electrodes
- ΔA - Change in cross-sectional area

$$\Delta V = L\,\Delta A = \frac{\rho_b L^2}{Z_b}$$

Impedance measurement



(b)

(c)

$$\Delta Z = [(Z_b || Z) - Z]$$

$$\Delta Z = \frac{-Z^2}{Z + Z_b}$$

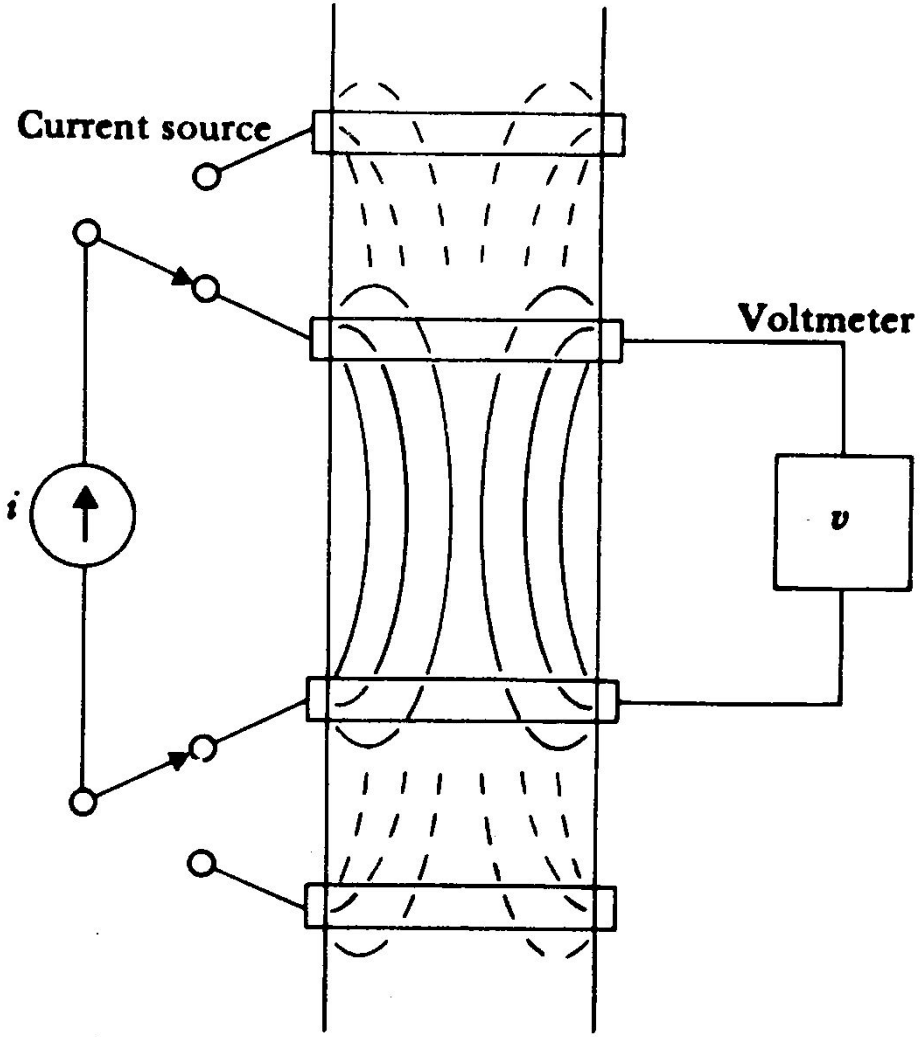
Impedance measurement

$$Z \ll Z_b$$

$$\frac{1}{Z_b} \cong \frac{-\Delta Z}{Z^2}$$

$$\therefore \Delta V = \frac{-\rho_b L^2 \Delta Z}{Z^2}$$

Two-electrode & Four-Electrode impedance plethysmography



Two-electrode impedance plethysmography

- In a **two electrode system**, a constant current is forced through the tissue between the two electrodes, and the resulting voltages are measured.

Four-Electrode impedance plethysmography

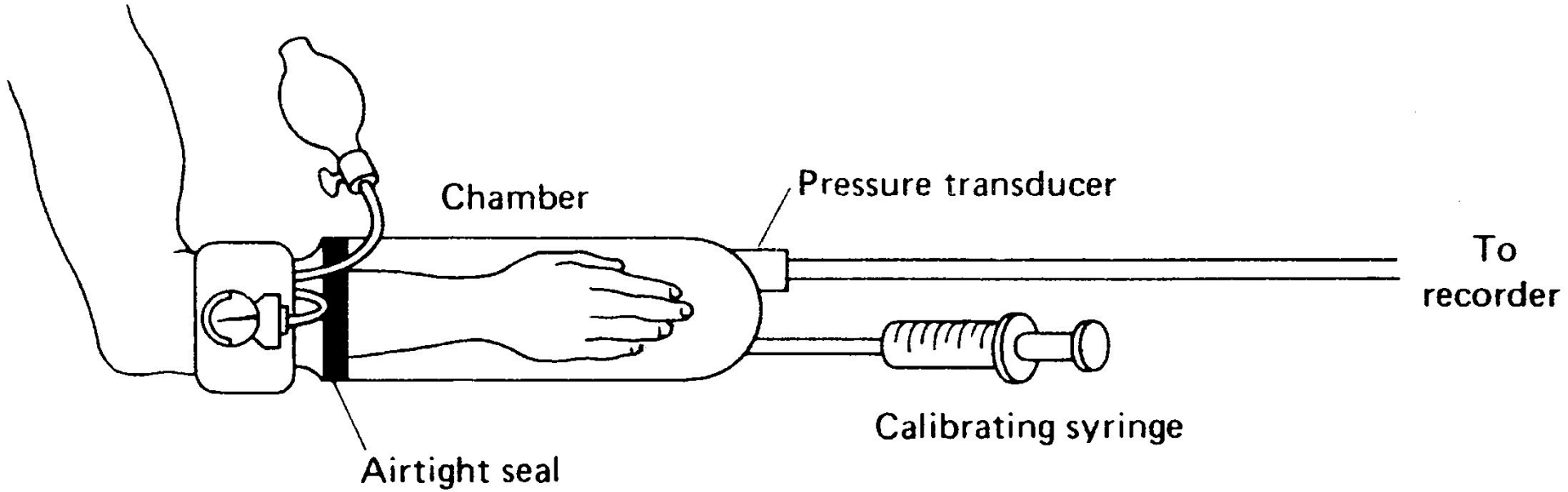
- In the **four-electrode system**, the constant current is forced through two outer, or current electrodes, and the voltage between the two inner, measurement, electrodes is measured.

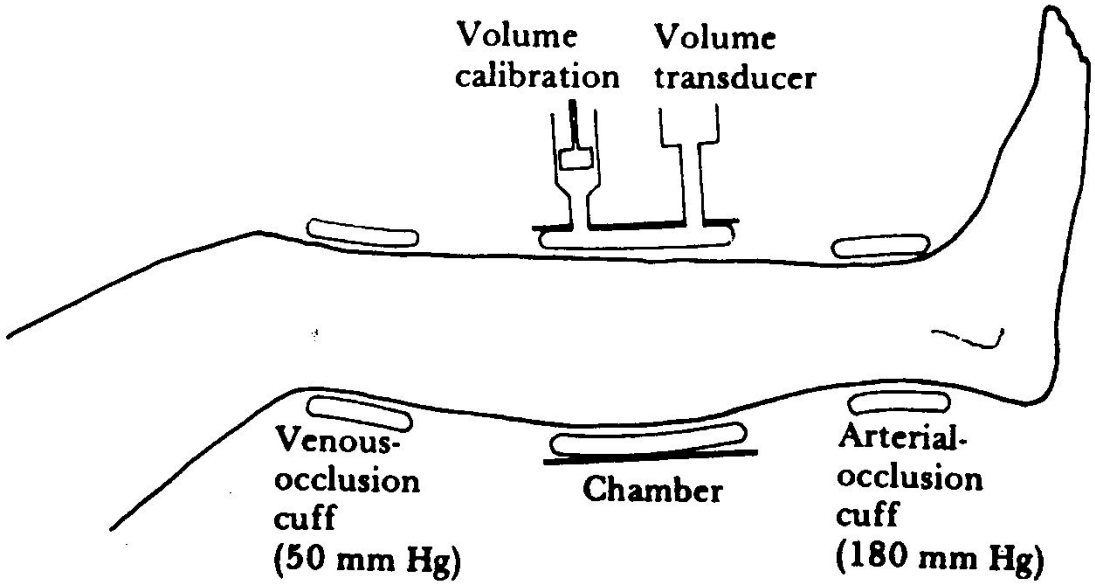
Advantages of Four-Electrodes impedance plethysmography

- Much smaller amount of current through the measuring electrodes which reduces the possibility of error due to changes in electrode resistance.

- Current density is more uniform in the region of interest.

Chamber Plethysmography





Chamber Plethysmography…

- Consists of a rigid cup or chamber placed over the limb or digit in which the volume changes are to be measured.

- The cup is tightly sealed to the member to be measured so that any changes of volume in the limb or digit reflect as pressure changes or volume change inside the chamber.

- Either fluid or air can be used to fill the chamber.

Chamber Plethysmography…

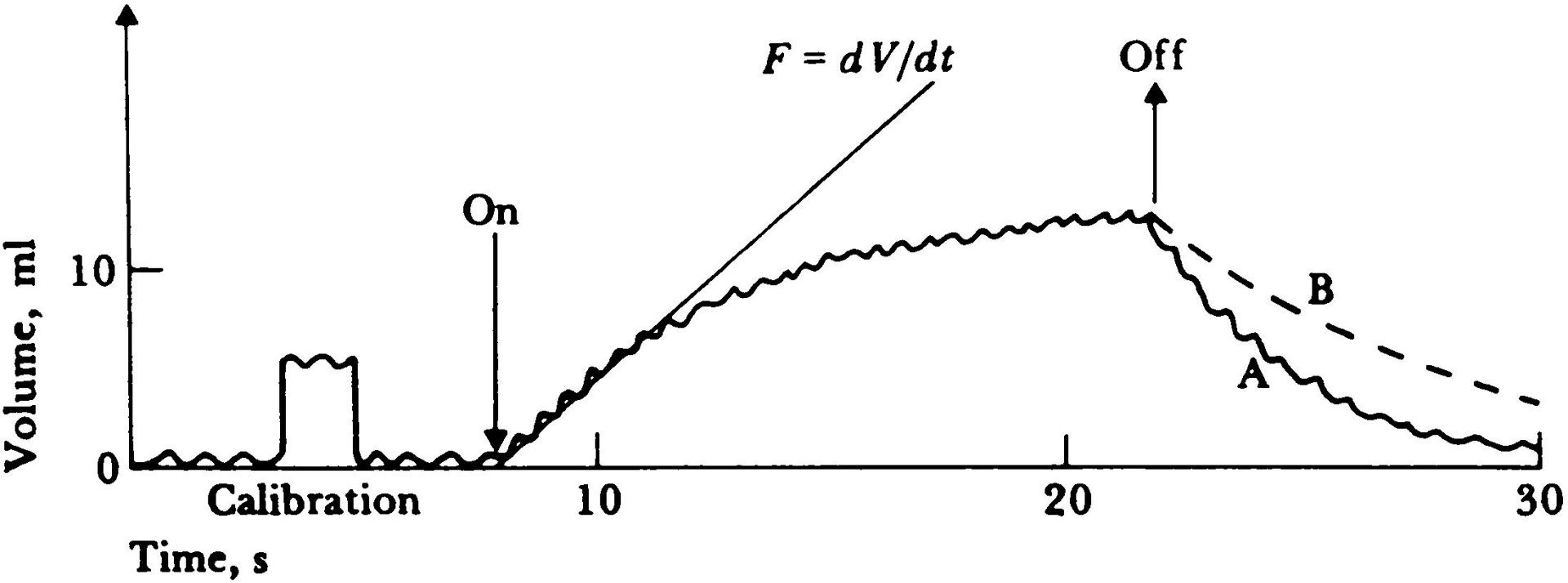
- By inflating the cuff to a pressure just above the venous pressure, arterial blood can flow past the cuff, but venous blood cannot leave.

- As a result, the limb or digit increases its volume with each heartbeat by the volume of the blood entering during that beat.

Chamber Plethysmography…

- A pressure or displacement transducer is included to provide a signal that can be calibrated to represent the volume of the limb or digit.

Chamber Plethysmogram



- The slope of the line along the peaks of the pulsation represents the overall rate at which blood enters the limb or digit.

Photoplethysmogram

- A **photoplethysmogram** (**PPG**) is an optically obtained plethysmogram, a volumetric measurement of an organ. A PPG is often obtained by using a pulse oximeter which illuminates the skin and measures changes in light absorption.

- A conventional pulse oximeter monitors the perfusion of blood to the dermis and subcutaneous tissue of the skin.

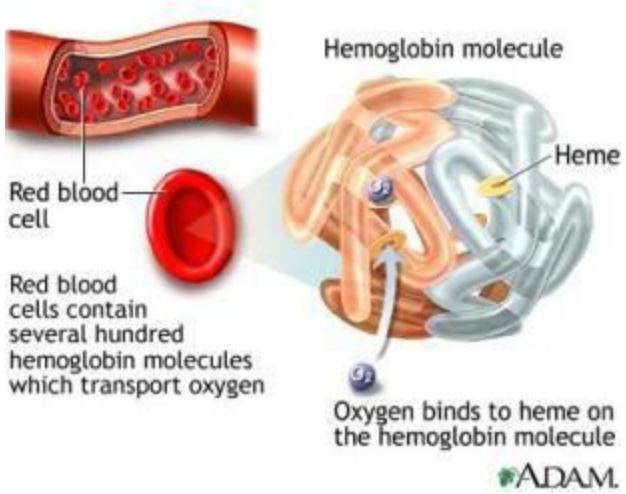
The need for real-time oxygen saturation monitoring

- Respiratory failure & pulmonary disease
- Intensive care (especially neonatal)
- Anaesthesia:

  A study of critical incidents in 4979 anaesthetics showed that an “unexpected physiological deterioration requiring intervention” occurred in 191 of the cases. *Oxygen desaturation was the most common underlying change (151 events) occurring prior to or during the physiological event, thus providing a first warning of the impending event.*

Oximetry

- Oximetry is a technique for measuring how much oxygen the blood is carrying, the *oxygen saturation of the blood.*
- The oxygen saturation of *arterial blood is a very useful parameter for clinicians to know, especially in patients with respiratory disorders:*
  1. Oxygen is the most acutely necessary substrate for aerobic life.
  2. Insufficiency of oxygen (*hypoxia) leads to devastating neurological handicaps, if not death.*



Definition of oxygen saturation

$$SaO_2 = \frac{[HbO_2]}{[Total\ Haemoglobin]}$$

HbO_2 = Oxyhaemoglobin

- Note: When arterial oxygen saturation (SaO2) is measured non-invasively using pulse oximetry (see later), it is usually referred to as SpO2 - la **Oxygen Saturation**

Measuring oxygen saturation

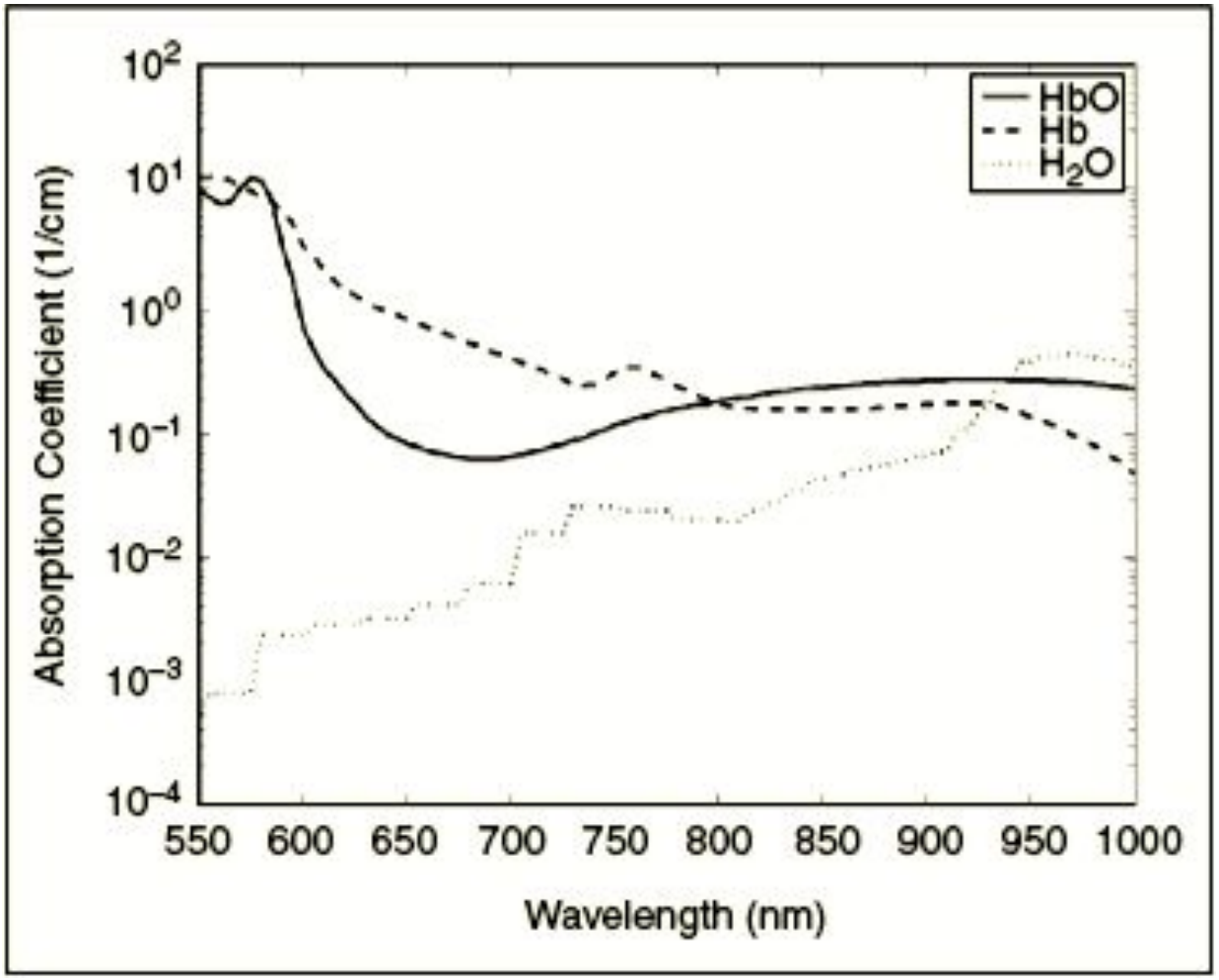
Is it possible to measure (arterial) SaO_2 without taking a blood sample?

Measuring oxygen saturation

Is it possible to measure (arterial) SaO_2 without taking a blood sample?

- The haemoglobin molecule in the red blood cells carries oxygen around the body.
- The haemoglobin molecule gives blood its distinctive colour.
- The two forms of the molecule (Hb and HbO_2) have different absorption spectra.

Absorption Spectra of Hb, HbO2 and H2O

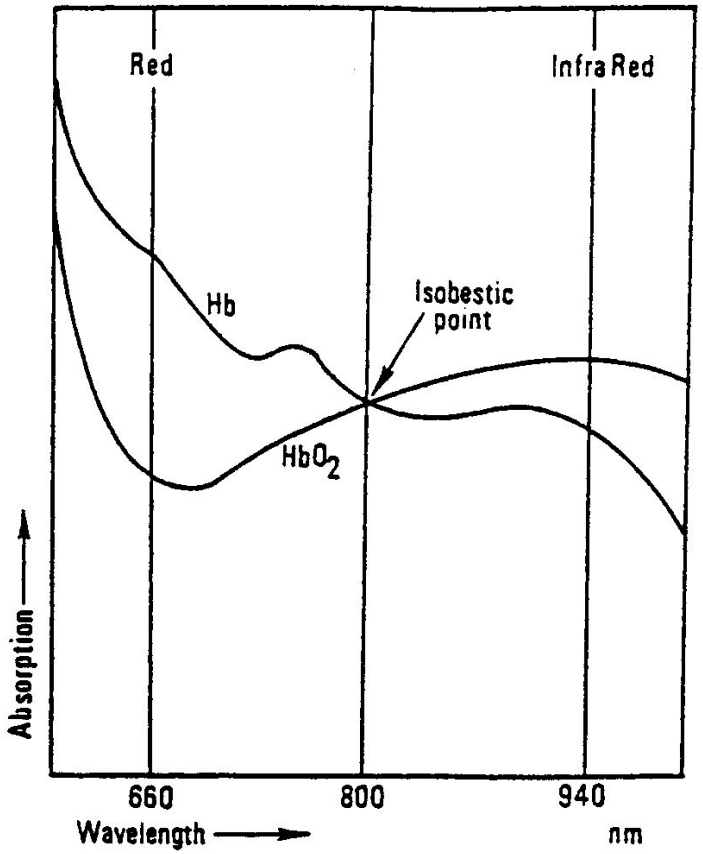


Measuring oxygen saturation

There is window of opportunity :

- The wavelength range between 600 and 1,000 nm is also the range for which there is the least attenuation of light by body tissues.
- By measuring the light transmission through a body segment at two wavelengths within that range, the arterial SaO2 can be determined.

Oximetry is a non-invasive optical technique

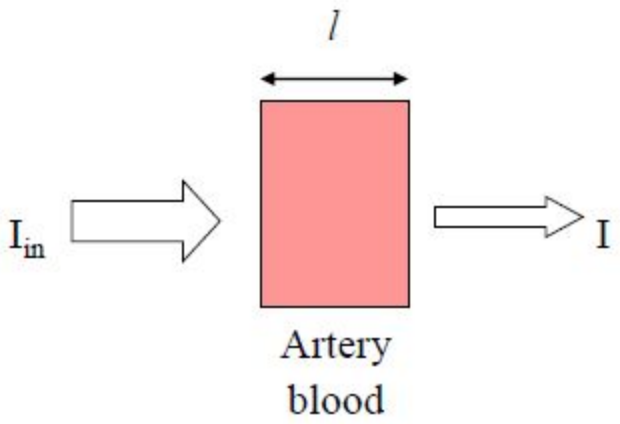


Attenuation of light through an artery

- According to Beer-Lambert Law:

$$I_1 = I_{in1} 10^{-(\alpha_{o1} C_o + \alpha_{r1} C_r) l}$$

$$I_2 = I_{in2} 10^{-(\alpha_{o2} C_o + \alpha_{r2} C_r) l}$$



where:
Co is the concentration of oxyhaemoglobin (HbO2)
Cr is the concentration of reduced haemoglobin (Hb)
αon is the absorption coefficient of HbO2 at wavelength *λn*
αrn is the absorption coefficient of Hb at wavelength *λn*

Calculating oxygen saturation

- Simple manipulation gives:

$$SaO_2 = \frac{C_0}{C_0 + C_r} = \frac{\alpha_{r2} R - \alpha_{r1}}{(\alpha_{r2} - \alpha_{o2}) R - (\alpha_{r1} - \alpha_{o1})}$$

where

$$R = \frac{\log_{10}(I_{in1} / I_1)}{\log_{10}(I_{in2} / I_2)}$$

- The above equation simplifies further if λ2 is chosen to be the *isobestic wavelength, i.e.* $\alpha r2 = \alpha o2$

Problems with oximetry

$$I_1 = I_{in1} 10^{-(\alpha_{o1} C_o + \alpha_{r1} C_r) l}$$

- Light is attenuated not only by arterial blood but also by:
  - Venous blood
  - Capillary blood
  - Skin
  - Other tissues

A brief history of oximetry

- Matthes, 1935
  - Transillumination of the earlobe at two wavelengths
  - No differentiation between arterial, venous and capillary blood
- Goldie, 1942
  - Compression of earlobe to obtain "bloodless" reference
- Millikan, 1942
  - Local heating to arterialise capillary blood
- Merrick and Hayes, 1976
  - Hewlett-Packard multi-wavelength oximeter

Hewlett-Packard Ear Oximeter

- Multi-component model of ear lobe
- Each light absorber assumed to act independently of the others
- Measurement of light transmission at eight wavelengths between 650 and 1050 nm
- Empirical calibration coefficients derived from study on 22 volunteers (750 data points)

Hewlett-Packard Ear Oximeter

- Disadvantages:
  - Complex instrumentation and signal processing
  - Need for pre-calibration
  - Ear must be heated to 41°C for arterialiation of capillary blood

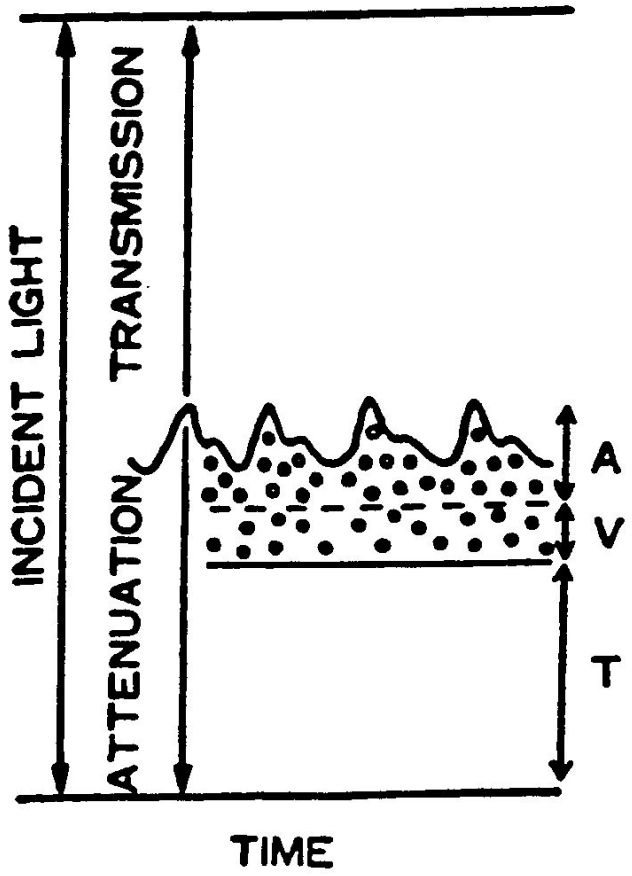
Problems with oximetry - summary

- It is hard to differentiate between absorption due to arterial blood and the absorption due to venous blood, skin tissue and bone.
- Two previous solutions:
  - Compression to obtain a bloodless measurement (not acceptable)
  - Complex model and even more complex instrument
- Today's solution: pulse oximetry

Pulse Oximetry

- Discovered in Japan (Aoyagi, 1974).
- Only that part of the signal directly related to the inflow of arterial blood into the body segment is used for the calculation of SaO2 or SpO2.
- It is assumed that the increase in attenuation of light is caused by the inflow of arterial blood only.

Pulse Oximetry

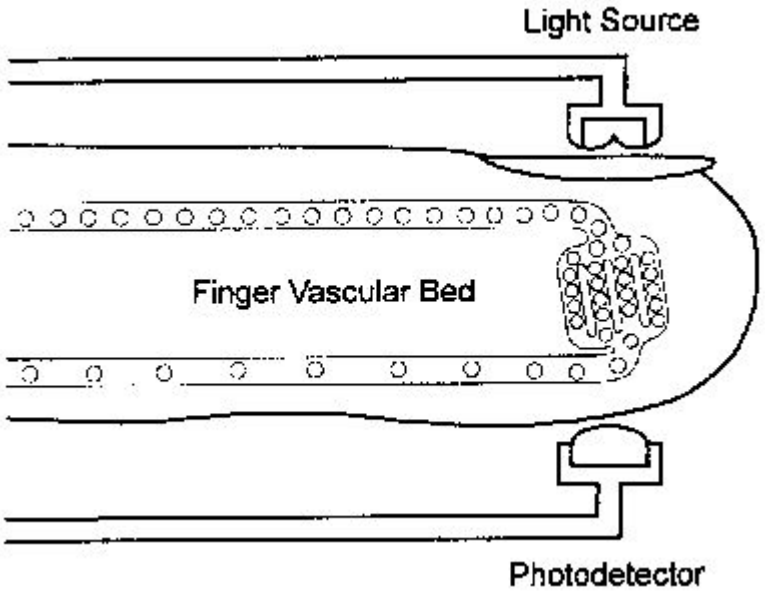


- Pulse oximetry assumes that the attenuation of light by the finger can be split into 3 independent components: arterial blood (A), venous blood (V) and tissues (T)
- The amplitudes of the pulsatile component of light attenuation at the two wavelengths are used to derive *arterial oxygen saturation*

Pulse Oximetry

- Development of LED/photodiode technology led to the pulse oximeter (~ 1980).
- Simple finger or earlobe probes (2 LEDs, one photodiode).
- Constant, non-invasive monitoring of SpO2.

Pulse Oximetry



- Light absorption across the finger (or the earlobe) is measured using a single probe with two LEDs and a photodiode

Calculation of oxygen saturation

- The first pulse oximeters used the simple oximetry equation to compute values of arterial SpO2.

Calculation of oxygen saturation

- If we define *R as:*

$$R = \frac{\log_{10}(I_{dc+ac}/I_{dc})_{\lambda 1}}{\log_{10}(I_{dc+ac}/I_{dc})_{\lambda 2}}$$

- Then the general oximetry equation given earlier is equally valid:

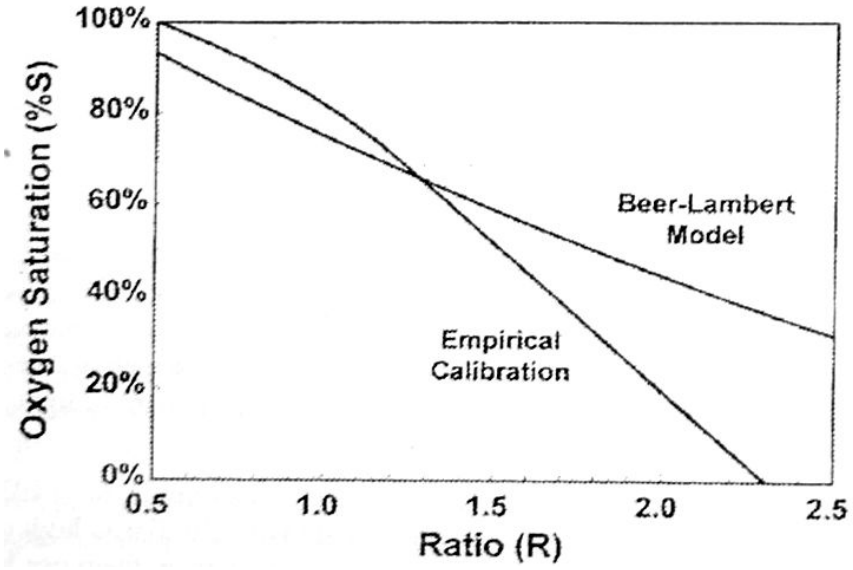
$$SaO_2 = \frac{C_0}{C_0 + C_r} = \frac{\alpha_{r2}R - \alpha_{r1}}{(\alpha_{r2} - \alpha_{o2})R - (\alpha_{r1} - \alpha_{o1})}$$

Calculation of oxygen saturation

- However, the Beer-Lambert law, on which it is based, does not take account of the scattering of light by the red blood cells in the arterial blood.

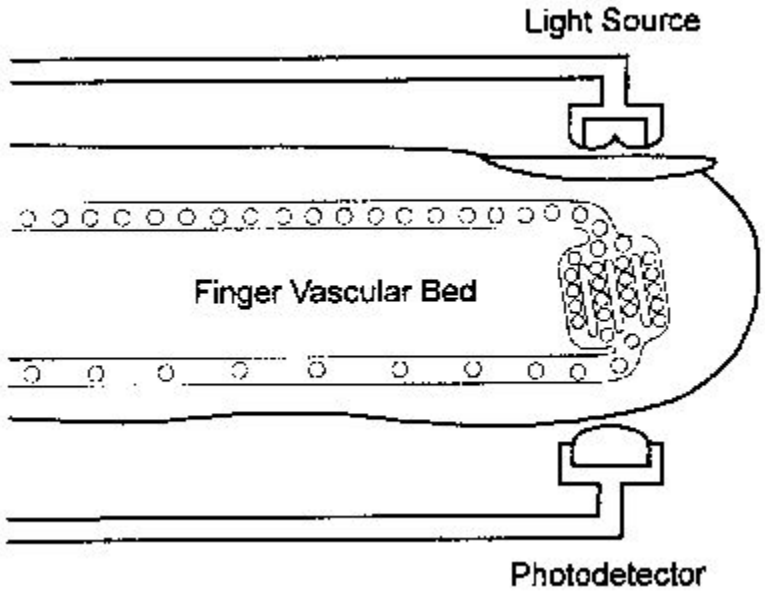
Calibration

- Beer-Lambert law does not take into account multiple scattering by red blood cells.
- Calibration with empirical data (from a large number of volunteers).



Pulse oximetry instrumentation

- Overall requirements:
  - Shine light through the finger or ear lobe

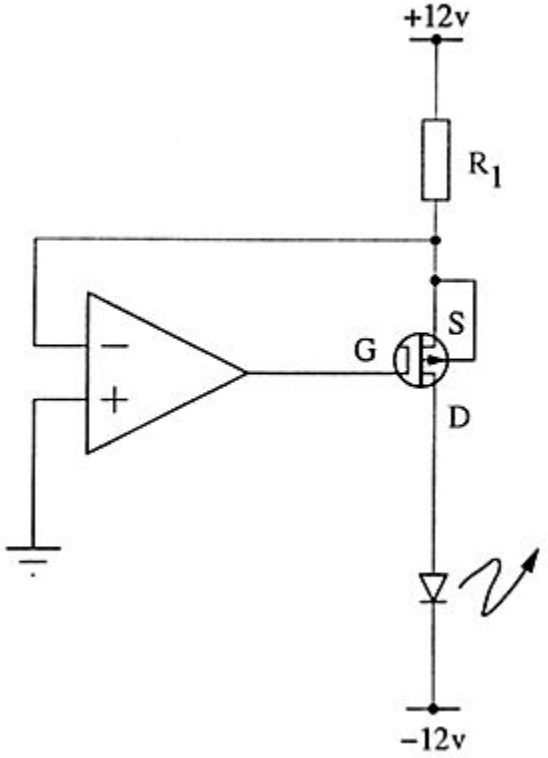


Pulse oximetry – light emission

- The requirement to shine light through the finger or earlobe dictates the use of small light emitting devices.
- Red (~ 660 nm) and Near Infra-Red (NIR, ~ 940 nm) wavelengths are used.
- Light Emitting Diodes (LEDs) are small and emit light at appropriate wavelengths:
  - Internal lensing to give a high intensity output
  - Pulse LEDs so that *peak power is increased*

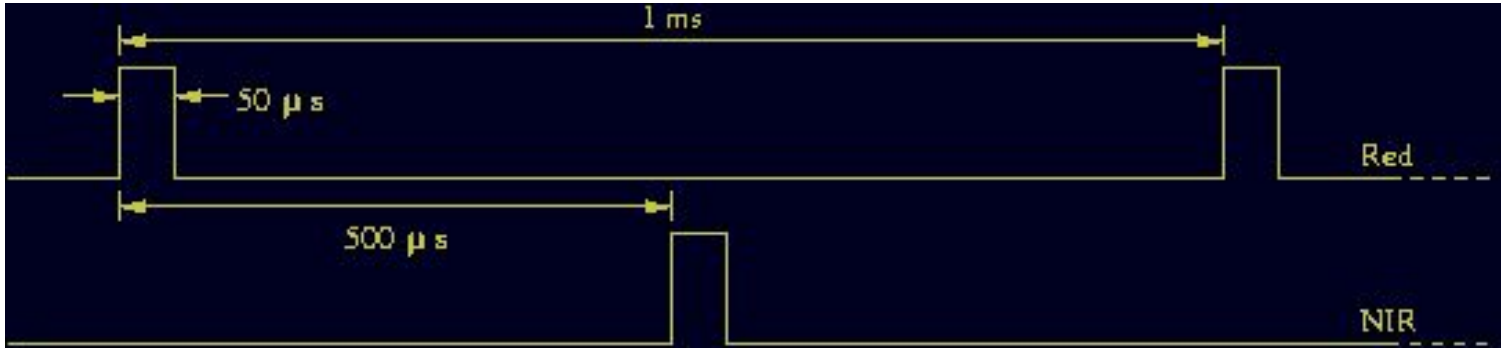
Pulse oximetry instrumentation

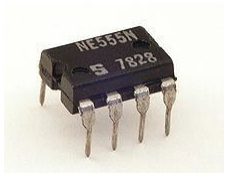
- Overall requirements:
  - Shine light through the finger or ear lobe (constant current source)
  - Control the pulsing of that light



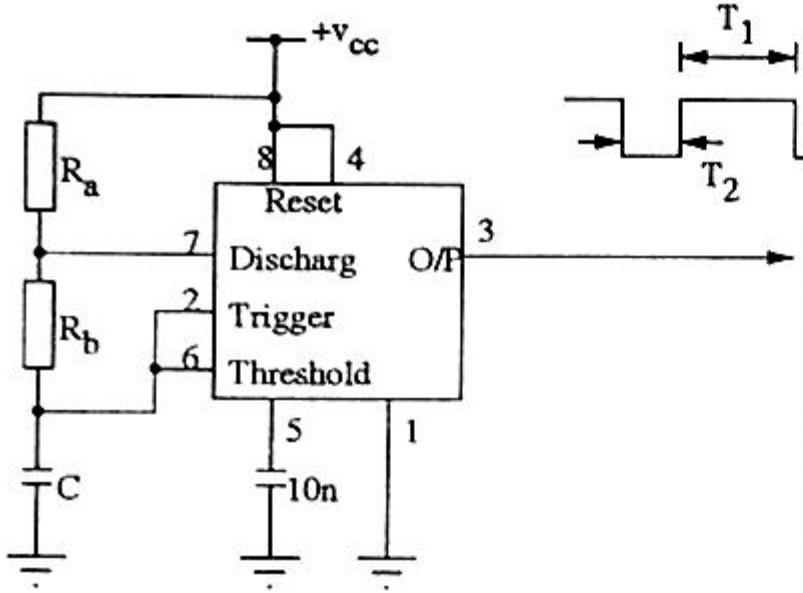
Timing of LED pulses

- The LEDs are pulsed for three reasons:
  - Increased peak power for same average power
  - Careful timing of the 'on' time for each LED allows a single photo-detector to be used for both LEDs
  - Reduces localised heating





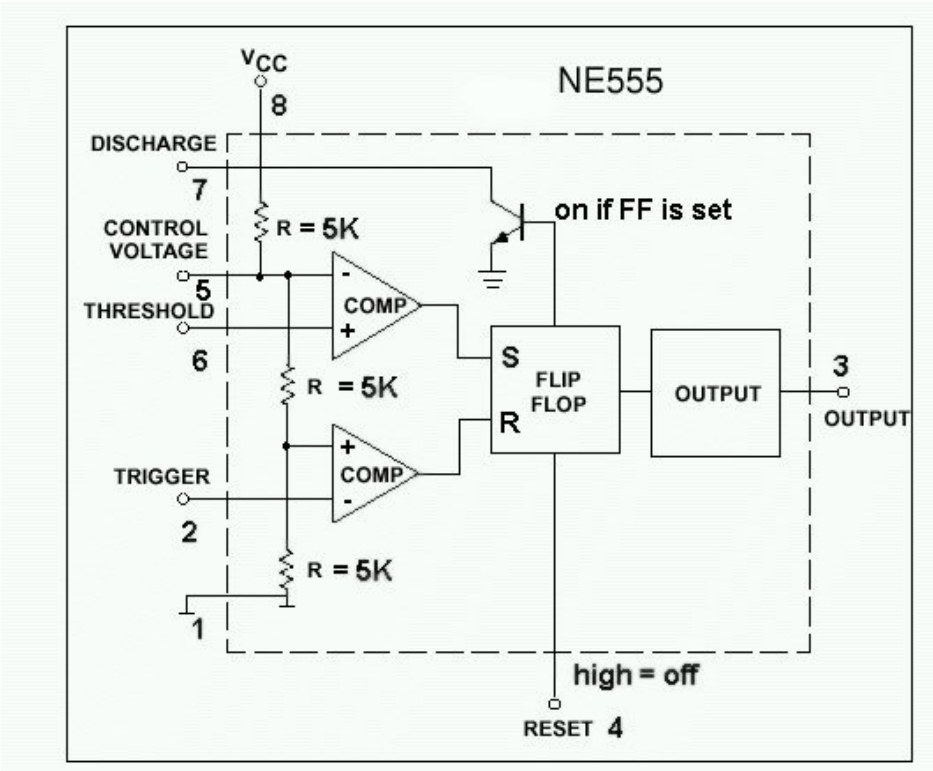
Timing circuit



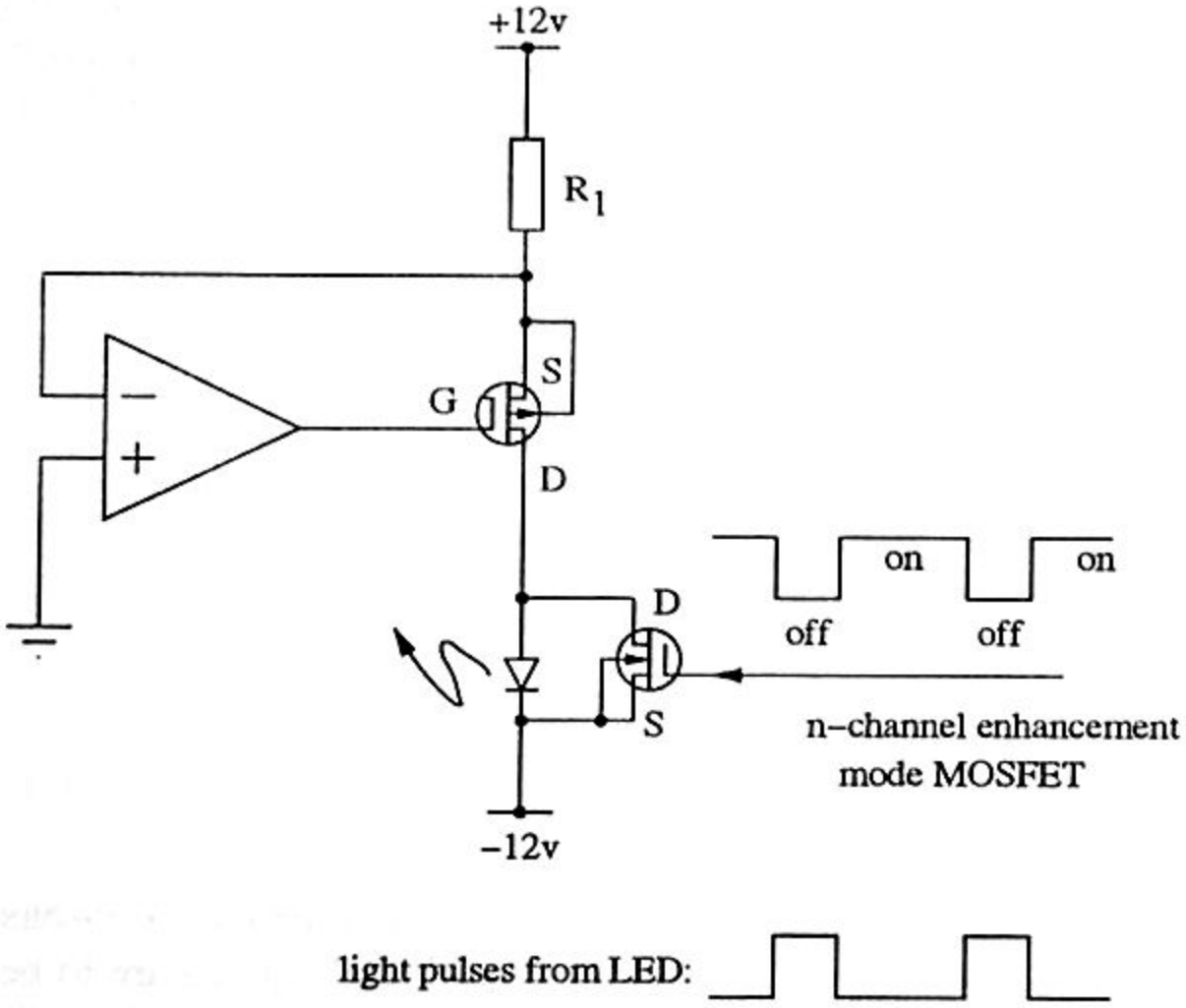
$$T_1 = 0.7(R_a + R_b)C$$

$$T_2 = 0.7\,R_b\,C$$

C = 22 nF, Ra = 56 kΩ and Rb=3.3 kΩ will give 50 μs pulse approximately every ms

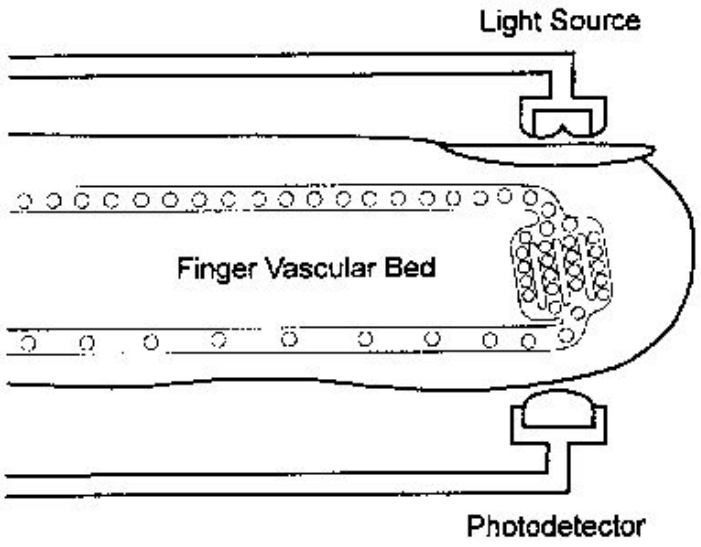


Pulsing the light output



Pulse oximetry instrumentation

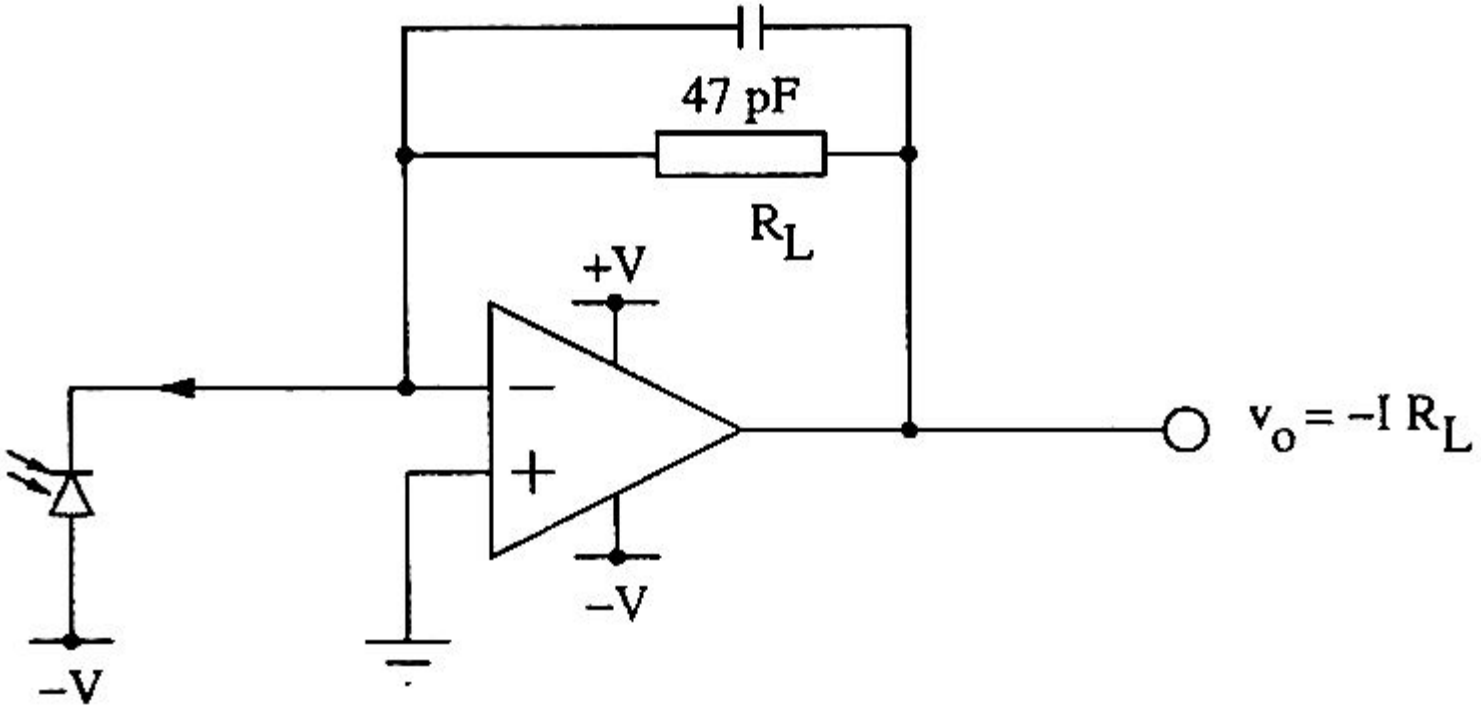
- Overall requirements:
  - Shine light through the finger or ear lobe
  - Control the pulsing of that light
  - Design appropriate light detection circuitry



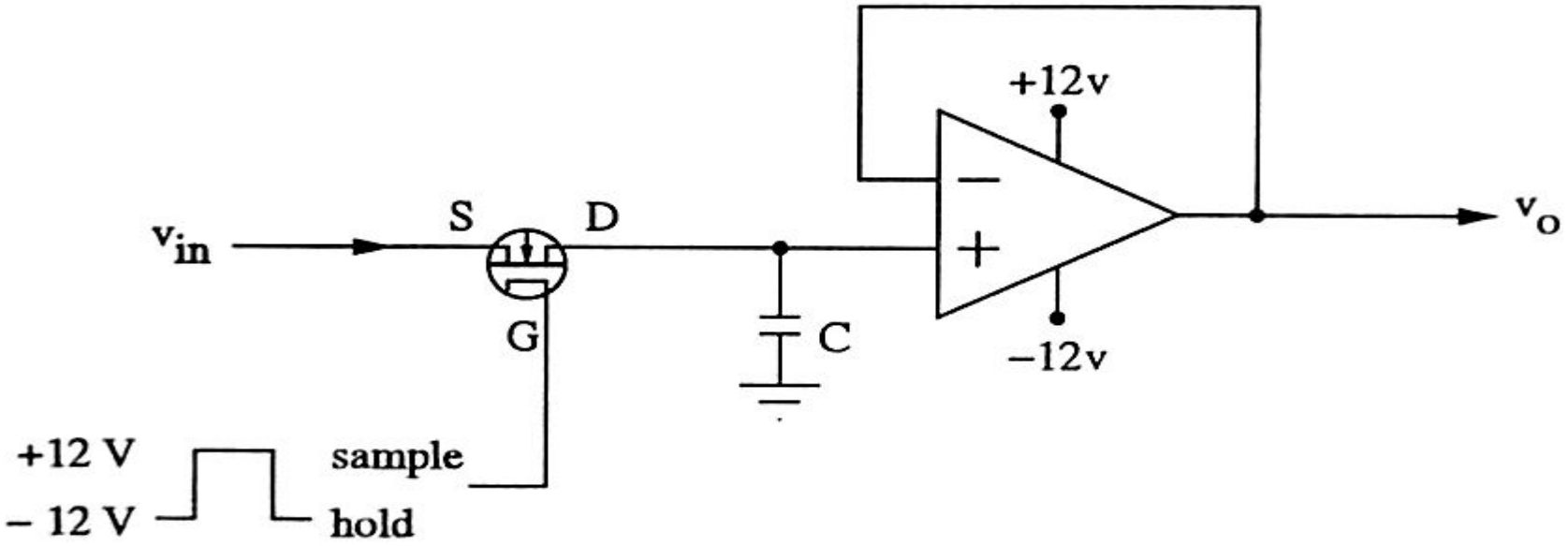
Light detection

- Photodiodes are the simplest solid-state optical detectors.
- When light falls on the p-n junction region, an electron-hole pair is created.
- The hole and the electron are swept in opposite directions.
- The resulting light current is seen as a large increase in the reverse current.
- This current is turned into a voltage, using an op-amp for current-to-voltage conversion.

Receiver circuit



Sample-and-hold circuit



- C should be as large as possible to minimise voltage droop during the hold phase.
- C should be as small as possible to allow high-frequency signals to be followed accurately during the sample phase.

Pulse oximetry instrumentation

- Overall requirements:
  - Shine light through the finger or ear lobe
  - Control the pulsing of that light
  - Design appropriate light detection circuitry
  - Sample and hold the received signal
  - Control the amplitude of the transmitted light

Automatic Gain Control

- There are three reasons why an AGC circuit is used in pulse oximetry:
  - It allows the spectral response of the photodiode to be compensated for.
  - It allows the d.c. level of both the NIR and the red signals to be kept at the same level (say 2V), regardless of the thickness or skin characteristics of the patient's finger.
  - It keeps the a.c. signal (which varies between 0.1% and 2% of the total signal) within a pre-defined range.

Pulse oximetry instrumentation

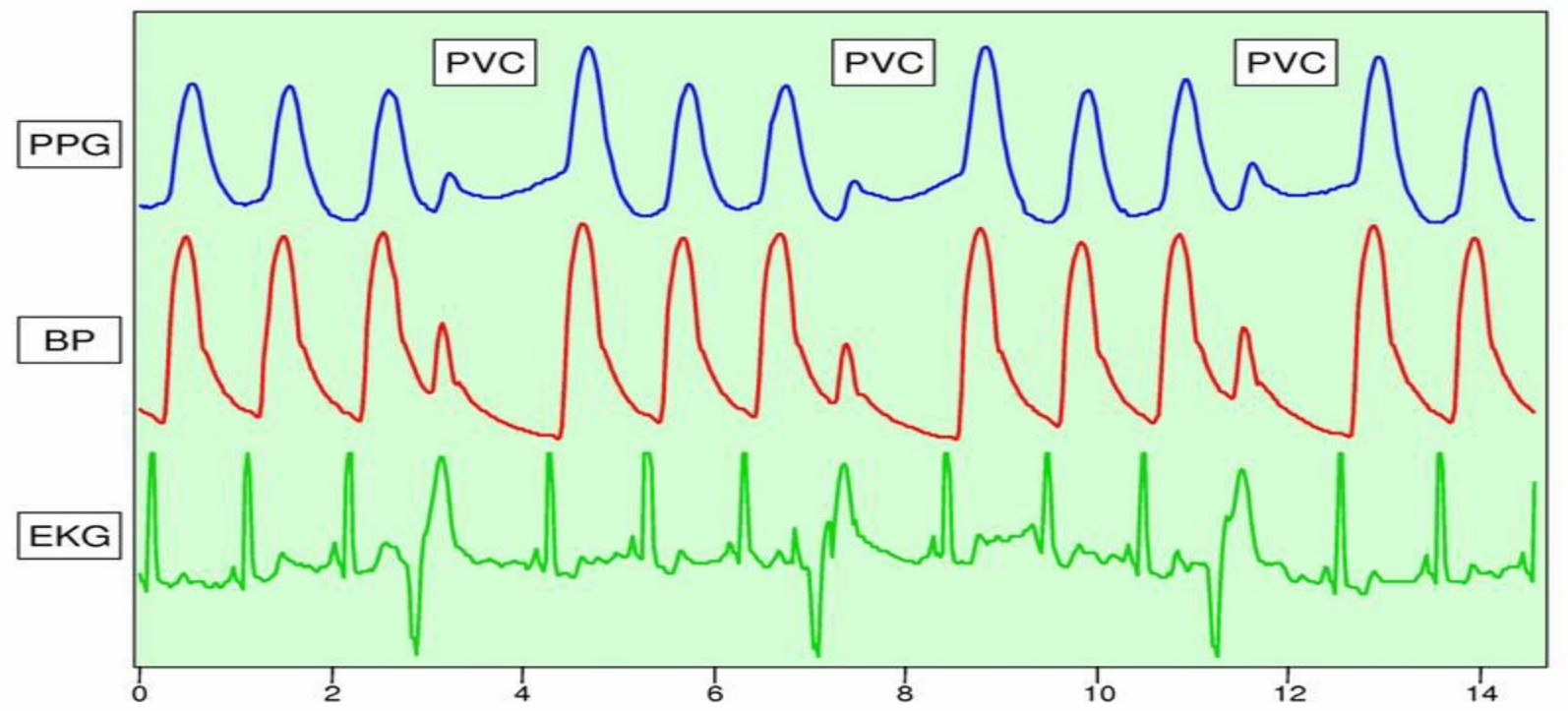
- Overall requirements:
  - Shine light through the finger or ear lobe
  - Control the pulsing of that light
  - Design appropriate light detection circuitry
  - Sample and hold the received signal
  - Control the amplitude of the transmitted light
  - Filter, store and interpret the information

Pulse oximetry instrumentation

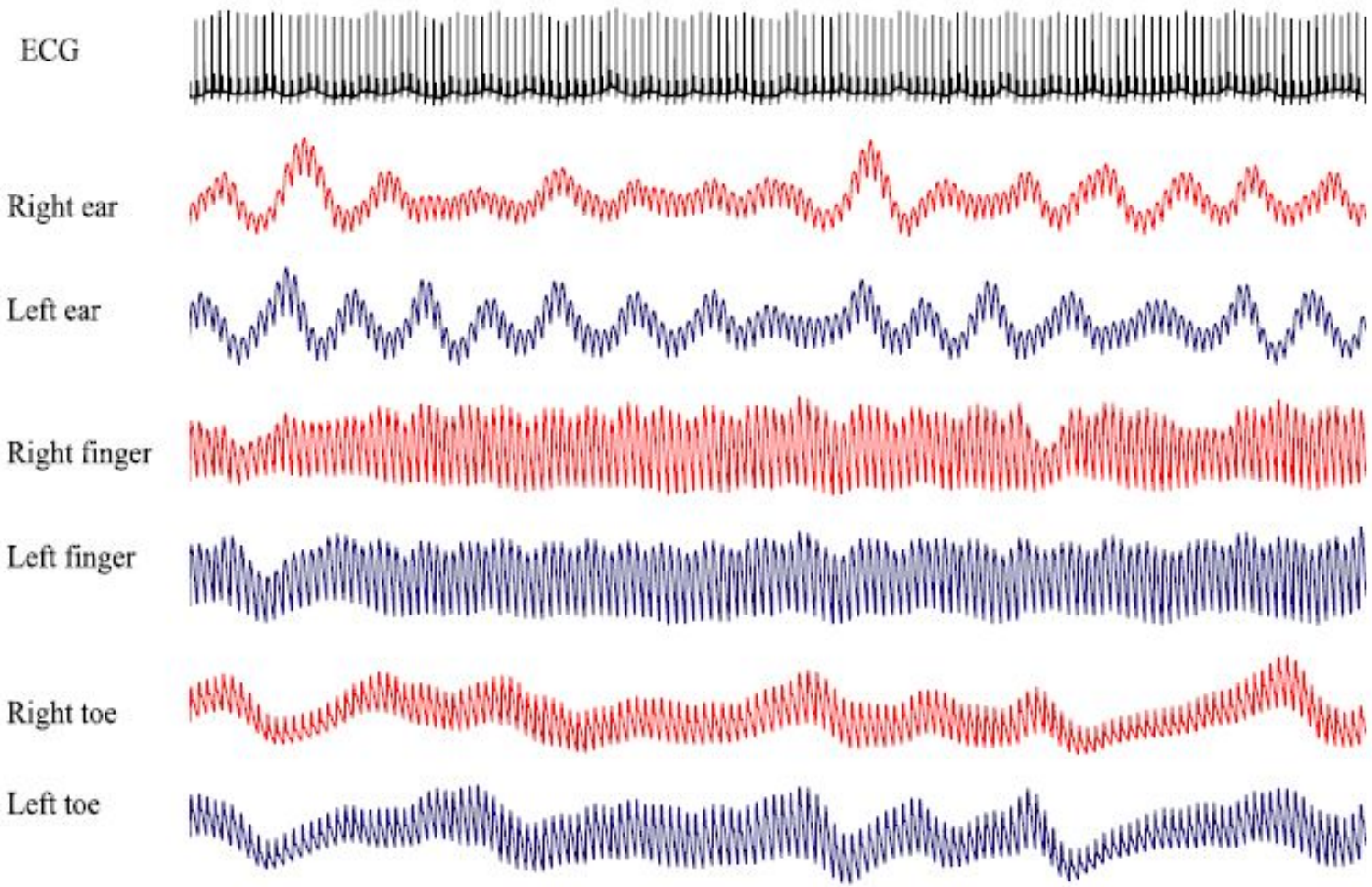
- Finally, a CPU of some description will be used to process the data.
- It will perform the following:
  - Further noise reduction (possibly using averaging)
  - Calculation of *R*
  - Calculation of SpO2 using a look-up table

Relative timing to ECG & BP

- ... and abnormal heart beats



Location of probe is important



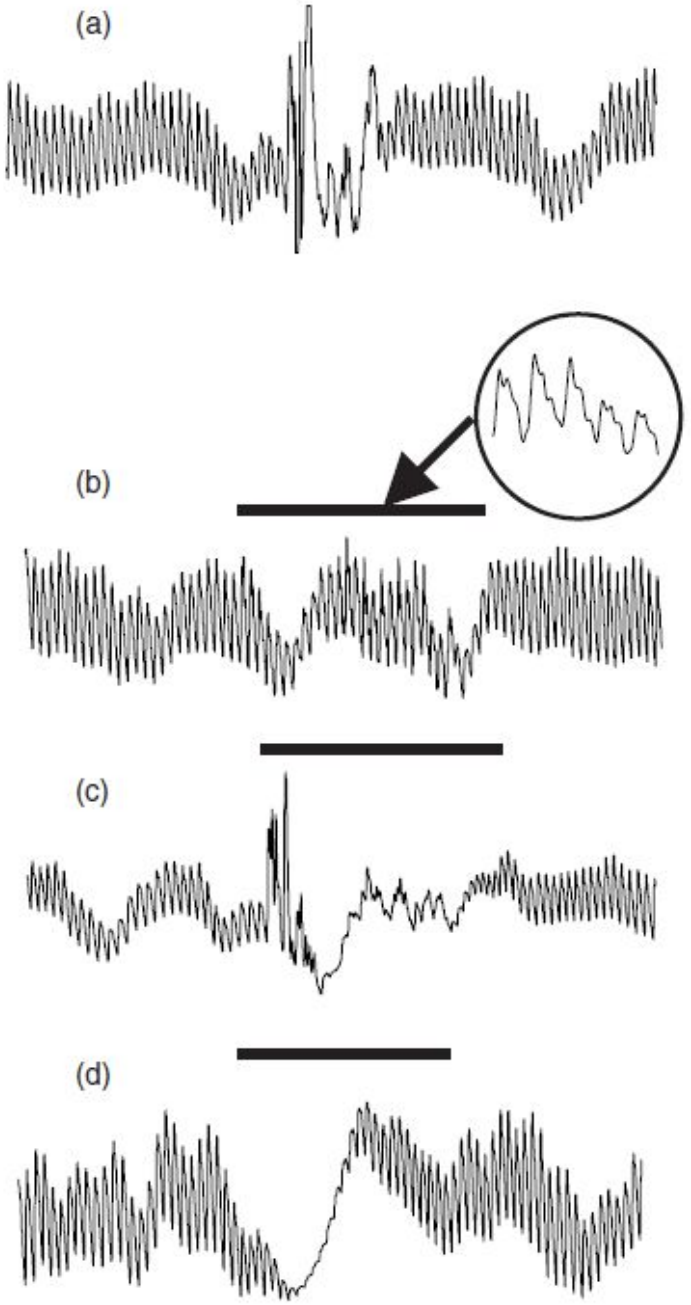
Artifacts

a.Movement artifact

b.Hand or finger tremor

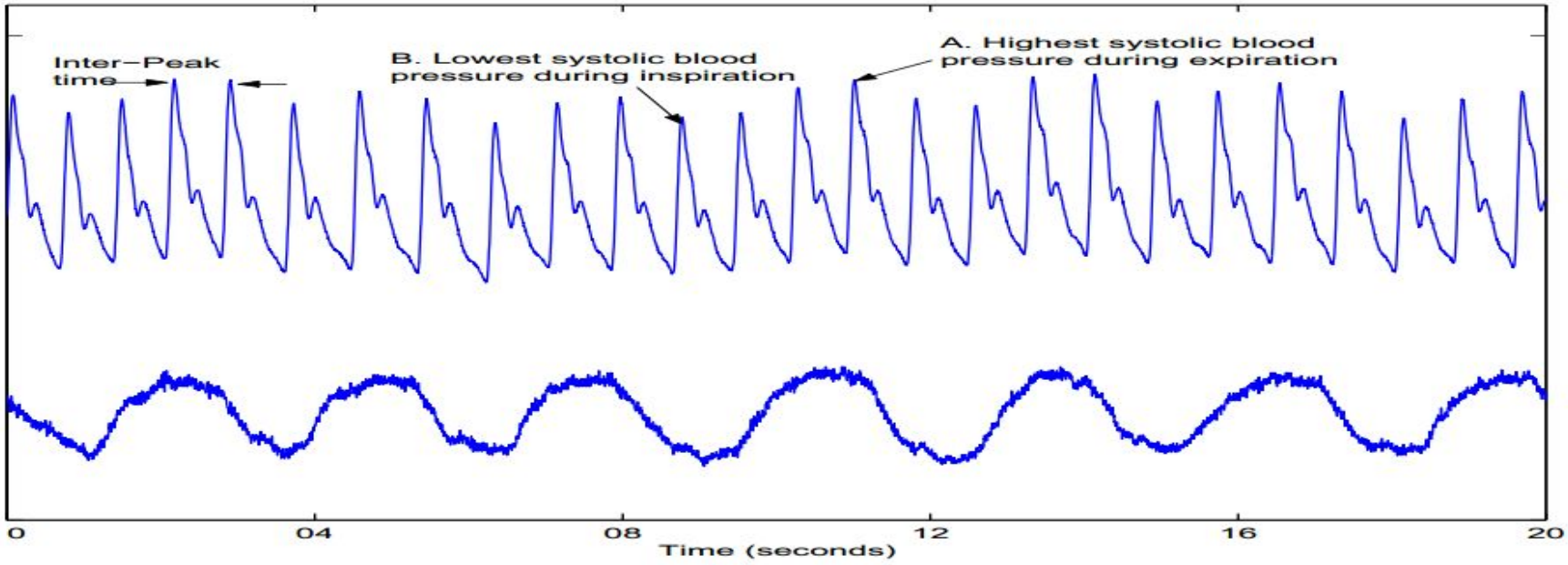
c.Coughing

d.Big breath



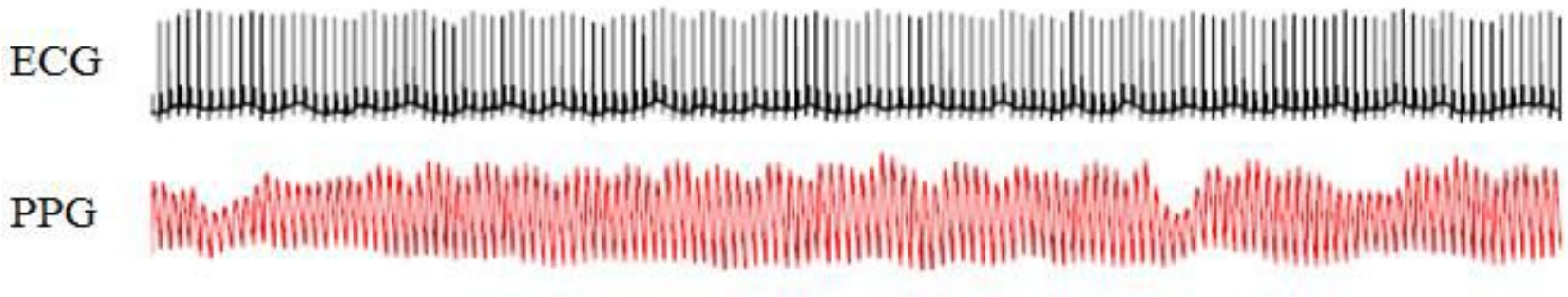
Artifacts can be useful

- Pulsus Paradoxus: the inspiratory decrease in systolic blood pressure which is proportional to changes in intrathoracic pressure during inspiration and expiration

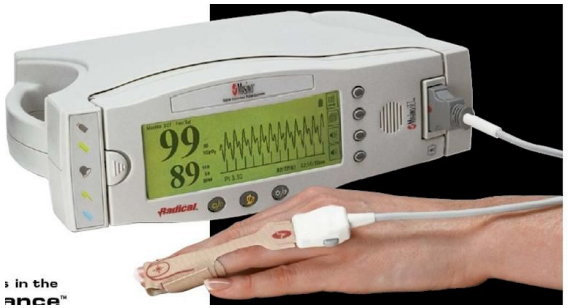


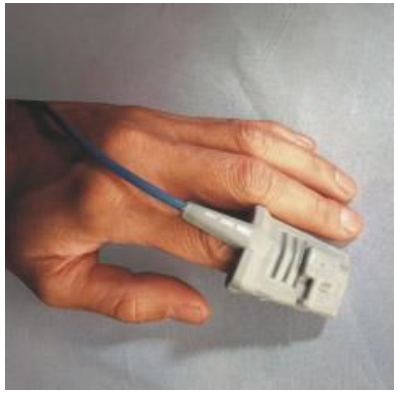
Artifacts can be useful

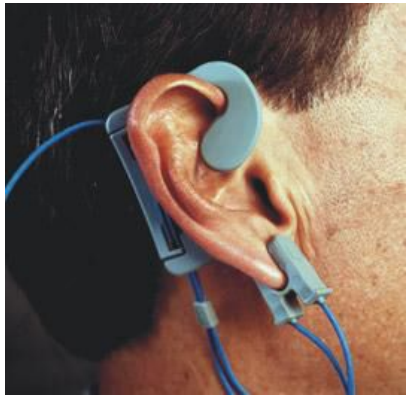
- Pulsus Paradoxus on the PPG
- Can be used to measure respiration
- Similar to ECG-derived respiration

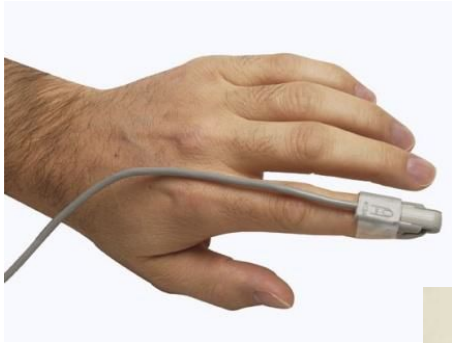


Commercial pulse oximeters & probes









Pulse oximetry

"The pulse oximeter is arguably the most significant technological advance ever made in monitoring the well-being and safety of patients during anaesthesia, recovery and critical care"

Severinghaus & Astrup (1986)

P.S. Modern SpO2 Design

- IC’s costing ~ $3

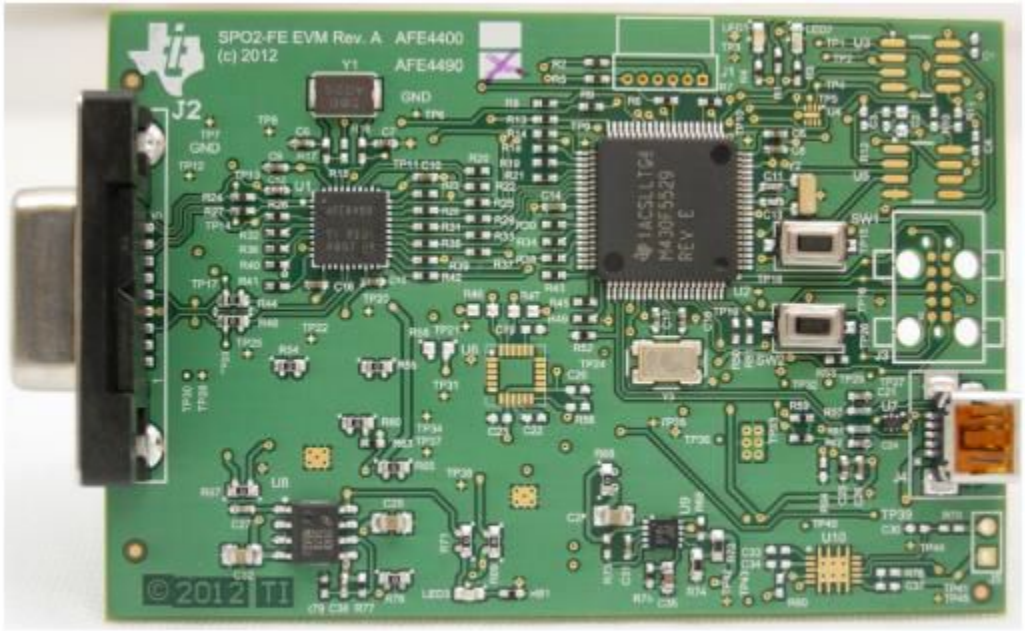


Figure AFE4490SPO2EVM Demonstration Kit

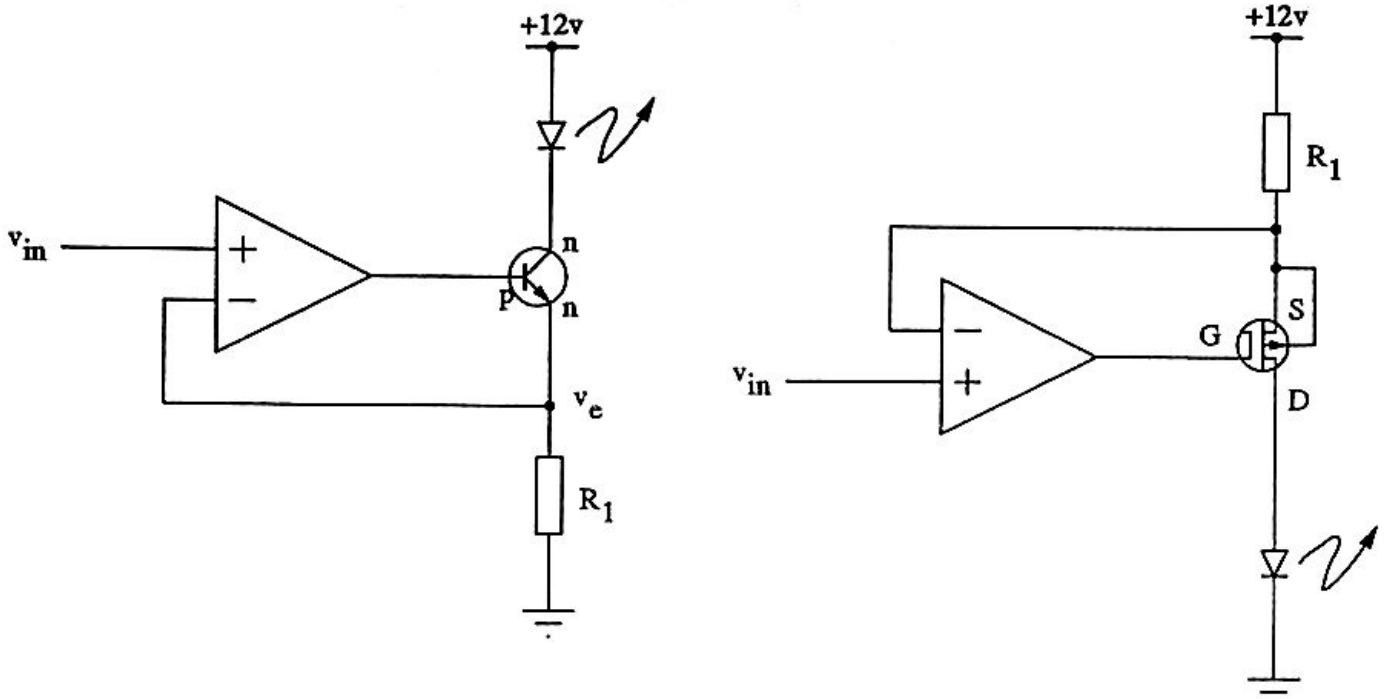
Applications

- Monitoring neonates: apnoea of prematurity

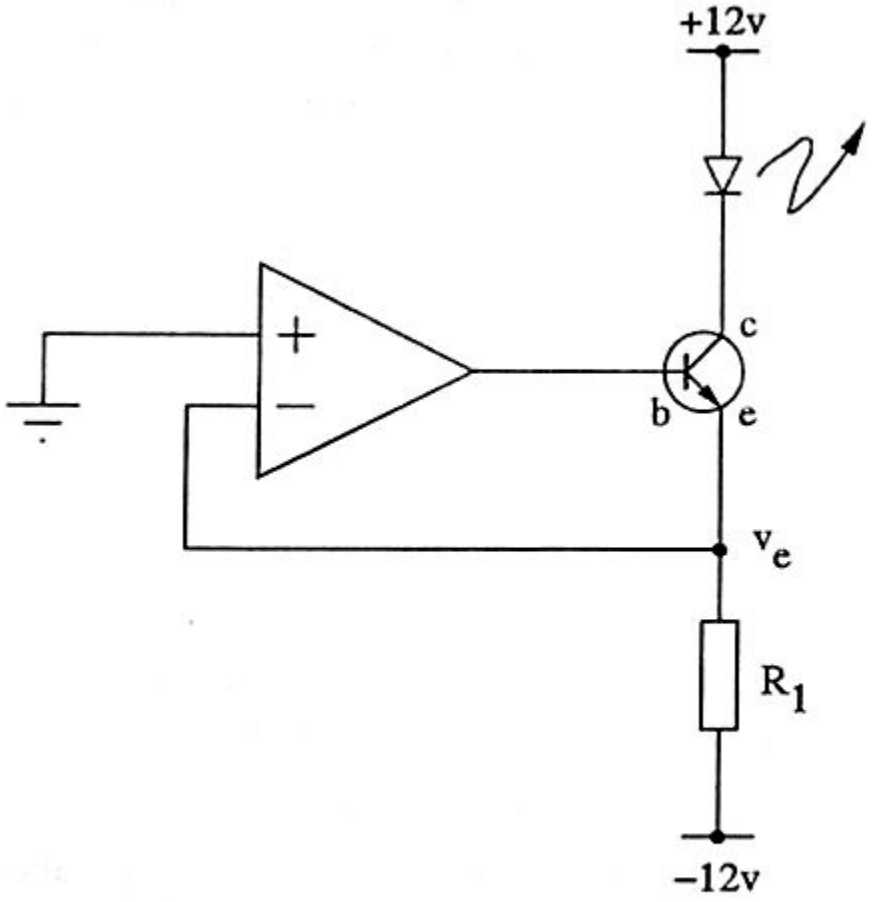
Appendix

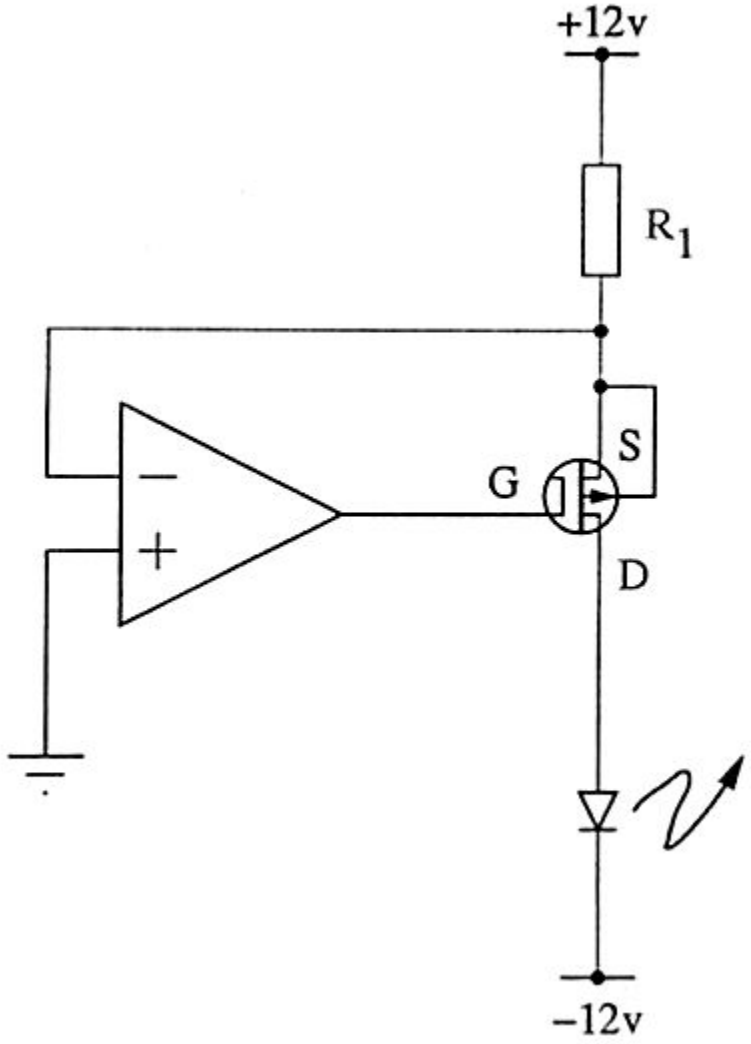
- Electronic design

  Constant current source



Alternative constant current circuit





Block diagram of pulse oximeter