Noninvasive Measurement of Arterial Oxygen Saturation by Pulse Oximetry

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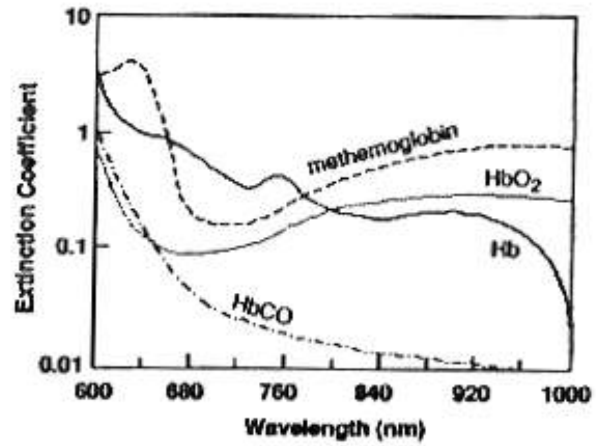
- Principles of Oximetry
- History of Oximetry
- Pulse Oximetry: Theory
- Pulse Oximetry: Instrumentation
- Clinical Applications and Limitations
- New Frontiers in Pulse Oximetry
- Research Directions
- Conclusions

- Hemoglobin changes color depending on its four states:

  oxyhemoglobin (HbO_2),
  deoxyhemoglobin (Hb),
  carboxyhemoglobin (HbCO), and
  methemoglobin (HbMet).

- Hemoglobin extinction coefficients:



- Measurement of hemoglobin concentrations

  Calibration requirement:

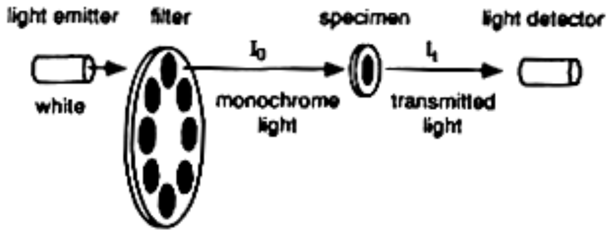
  Baseline: specimen with zero concentration
  Full scale: specimen with a known concentration

  Measurement requirement:

  At least 4 measurements at 4 different wavelengths to determine the 4 types of hemoglobin

Principles of Oximetry

- Light absorption for a specimen at different wavelengths can be measured by transmission spectrometry.



- Photons are transmitted, absorbed, reflected, or scattered:

$$I_0 = I_t + I_a + I_r + I_s$$

- Lambert-Beer law of light absorption (ignoring reflection and scattering):

$$I_t = I_0 e^{-\beta c z}$$

where

I_0: intensity of source light
I_t: light intensity detected
β: extinction coefficient, function of wavelength λ
c: concentration of hemoglobin
z: optical path length

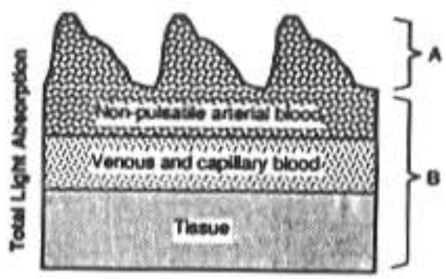
History of Oximetry

- 1864 - Hoppe-Syler observed the <u>color change of hemoglobin</u> when exposed to oxygen.
- 1934 - Kramer measured oxygen saturation of blood sample <u>in vitro</u> by transmission spectrometry.
- 1935 - Matthes developed the first noninvasive (nonpulsatile) oximeter for continuous measurement of oxygen saturation <u>in vivo</u> using two wavelengths of light.
- 1942 - Millikan developed a lightweight ear oximeter for airplane pilots and acknowledged problems with <u>zeroing and calibration</u>.
- 1948 - Wood and Geraci improved the infrared filter and used an inflatable balloon to stop blood flow for initial zeroing in an ear oximeter manufactured by Waters Company.
- 1960 - Hewlett-Packard introduced an ear oximeter featuring 8 wavelengths and self-calibration (Model 47201A).
- today - The 4-wavelength, self-calibrating co-oximeter is routinely used to measure the O_2 and CO saturation of a blood sample in vitro.

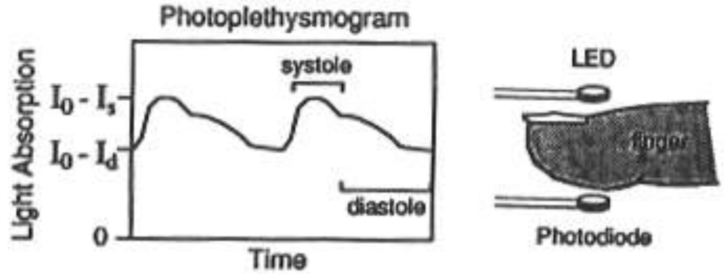
History of Pulse Oximetry

- 1975 - Nakajima et al. reported the feasibility of <u>pulse oximetry</u>, using the arterial blood pulsatile component to overcome calibration problem. The first pulse oximeter was manufactured by Minolta-Mochida (Model Oximet MET 1471).
- 1984 - Pulse oximeters were introduced to operating rooms and critical care units in the United States.
- 1989 - Pulse oximeters reached 95% of the operating rooms and manufactured by over 35 firms with annual world wide sales of 65,000 units valued at $200 million.
- today - Pulse oximeter is an essential instrument for patient monitoring - almost as important as the electrocardiography (ECG). Pulse oximetry has become a billion-dollar industry and is still growing.

Basic Idea - The pulsatile component in photo-plethysmogram is due to arterial blood alone, thus allowing for elimination of contributions from other absorbers such as venous/capillary blood and tissue.



Pulse Oximetry: Theory



First, assume there is only one type of hemoglobin.

$I_d = I_0 e^{-\beta c z_d}$ during diastole

$I_s = I_0 e^{-\beta c z_s} = I_0 e^{-\beta c (z_d + z)}$ during systole

$$I_d - I_s = I_0 e^{-\beta c z_d} - I_0 e^{-\beta c (z_d + z)}$$
$$= I_0 e^{-\beta c z_d} (1 - e^{-\beta c z})$$
$$A/B = \frac{I_d - I_s}{I_d} = 1 - e^{-\beta c z} \approx \beta c z$$

where A is the amplitude and B is the baseline component from the pulsatile photoplethysmogram. The last step is based on the series:

$$e^a = 1 + a + \frac{a^2}{2!} + \frac{a^3}{3!} + \cdots\cdots$$

and $\beta cz \ll 1$ because of small z.

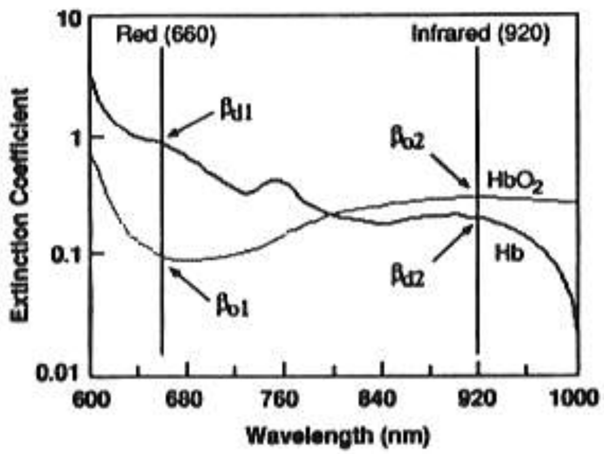
Next, assume there are only two types of hemoglobin: oxyhemoglobin with saturation x and deoxyhemoglobin with saturation (1-x).

$$A/B = \beta_o\, x\, c\, z + \beta_d\, (1 - x)\, c\, z = c\, z\, [\beta_o\, x + \beta_d\, (1 - x)]$$

Two measurements are required at two different wavelengths.

$$A_1/B_1 = c\, z\, [\beta_{o1}\, x + \beta_{d1}\, (1 - x)]$$

$$A_2/B_2 = c\, z\, [\beta_{o2}\, x + \beta_{d2}\, (1 - x)]$$



Forming the ratio of the above, we have

$$R = \frac{A_1/B_1}{A_2/B_2} = \frac{\beta_{o1}\, x + \beta_{d1}\, (1 - x)}{\beta_{o2}\, x + \beta_{d2}\, (1 - x)}$$

Solving for x, we have

$$x = \frac{R\, \beta_{d2} - \beta_{d1}}{\beta_{o1} - \beta_{d1} - R(\beta_{o2} - \beta_{d2})}$$

The above derivation is based on the assumptions:

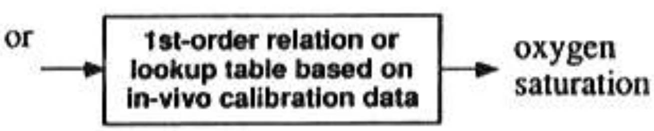
- monochrome light
- no scatter
- only two types of hemoglobin (HbO_2, Hb)
- ignoring venous pulsation

In reality, all four types of hemoglobin exist in normal human arterial blood:

HbO_2	90-100 %
Hb	0-10 %
HbCO	< 2 %
HbMet	< 1 %

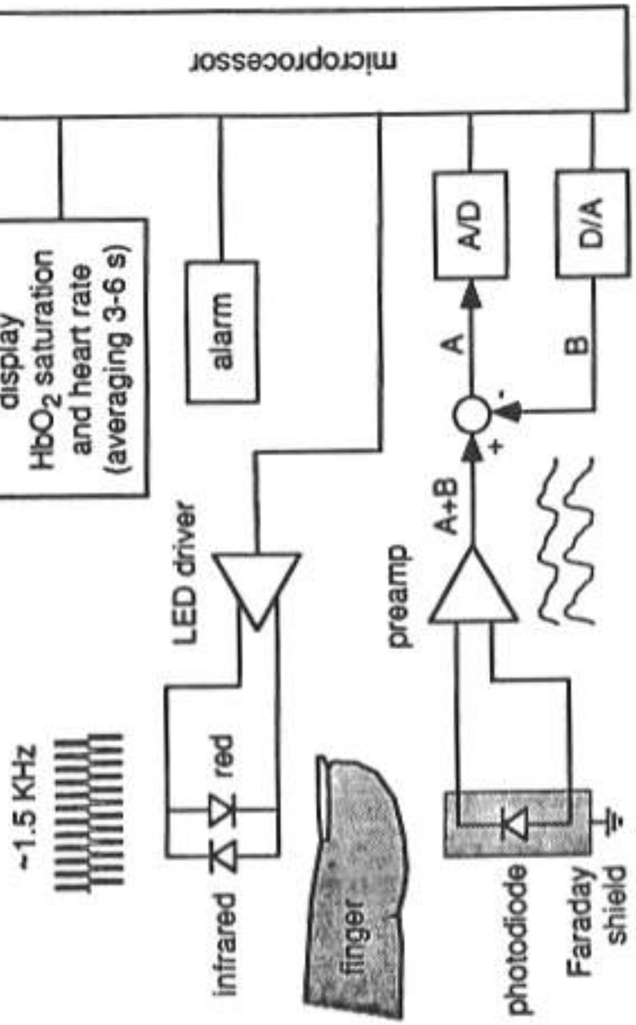
Despite the elegant derivation above, most practical systems rely on empirical data.

$$R = \frac{A_1/B_1}{A_2/B_2} \text{ or } R = A_1/A_2$$



Accuracy: 2% error for oxygen saturation between 70-99%

Pulse Oximetry - Instrumentation



Pulse Oximetry: Clinical Applications

Hypoxia detection and quantification during anesthesia and critical care for adults as well as neonates. Whereas the safe degree of hypoxia varies among individuals, typical ranges for monitoring purpose are:

Normal	90 - 100%
Mild hypoxemia	85 - 90%
Severe hypoxemia	<85%

HbO_2 saturation is a sensive indicator for hypoxia as shown by the rapid decline below the 90% "knee" point on the HbO_2 dissociation curve.