DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA

POLITECNICO DI MILANO



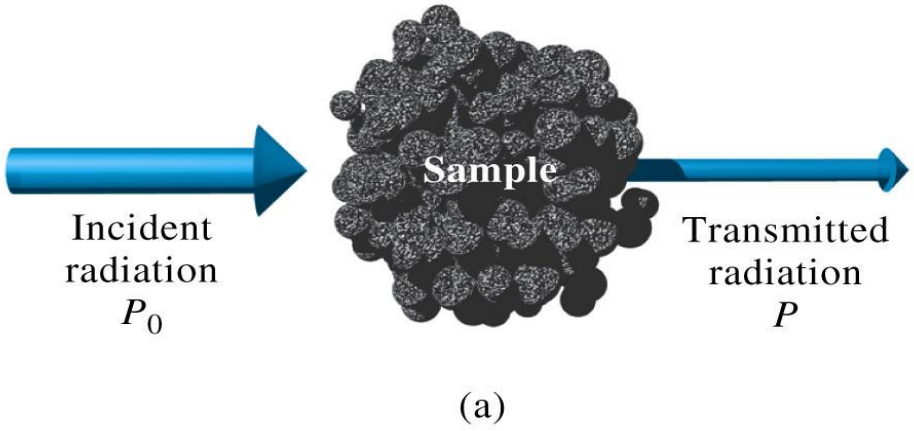


Lecture 13
Optical measurements: (Pulse-) Oximetry

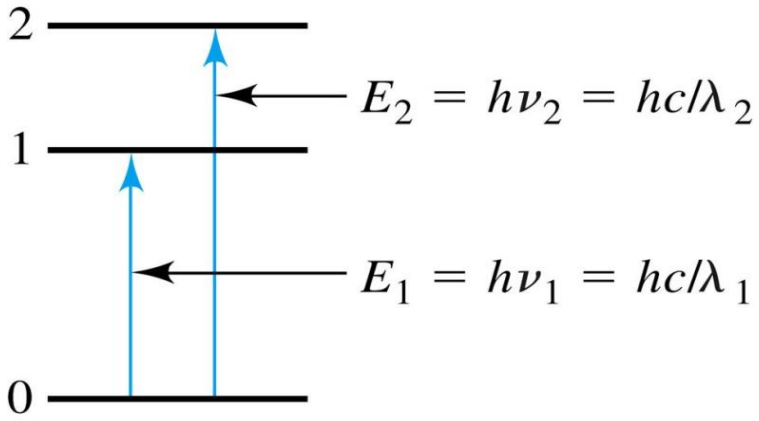
P0(lambda) --> [] ---> P(lambda)

EM waves-matter interaction : ABSORPTION

Radiation passes through a sample, and part of the power is absorbed

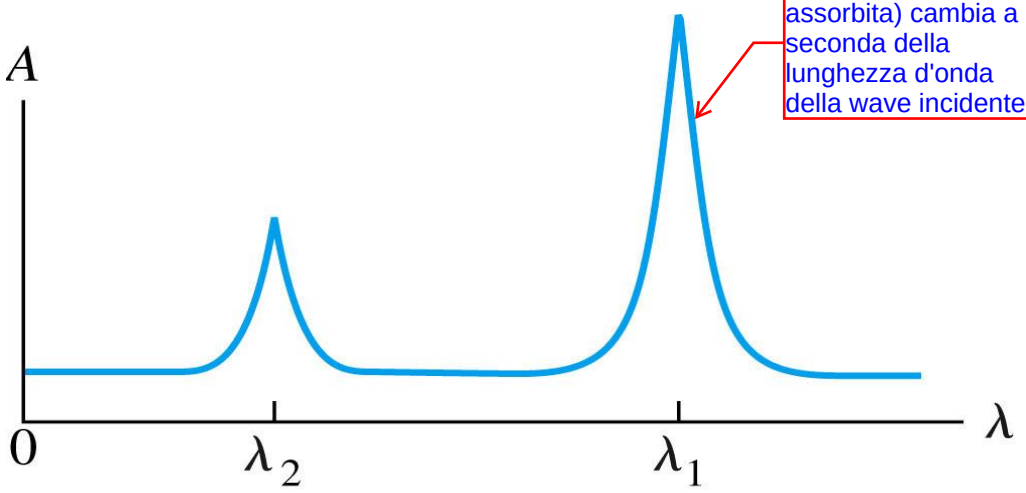


(a)



(b)

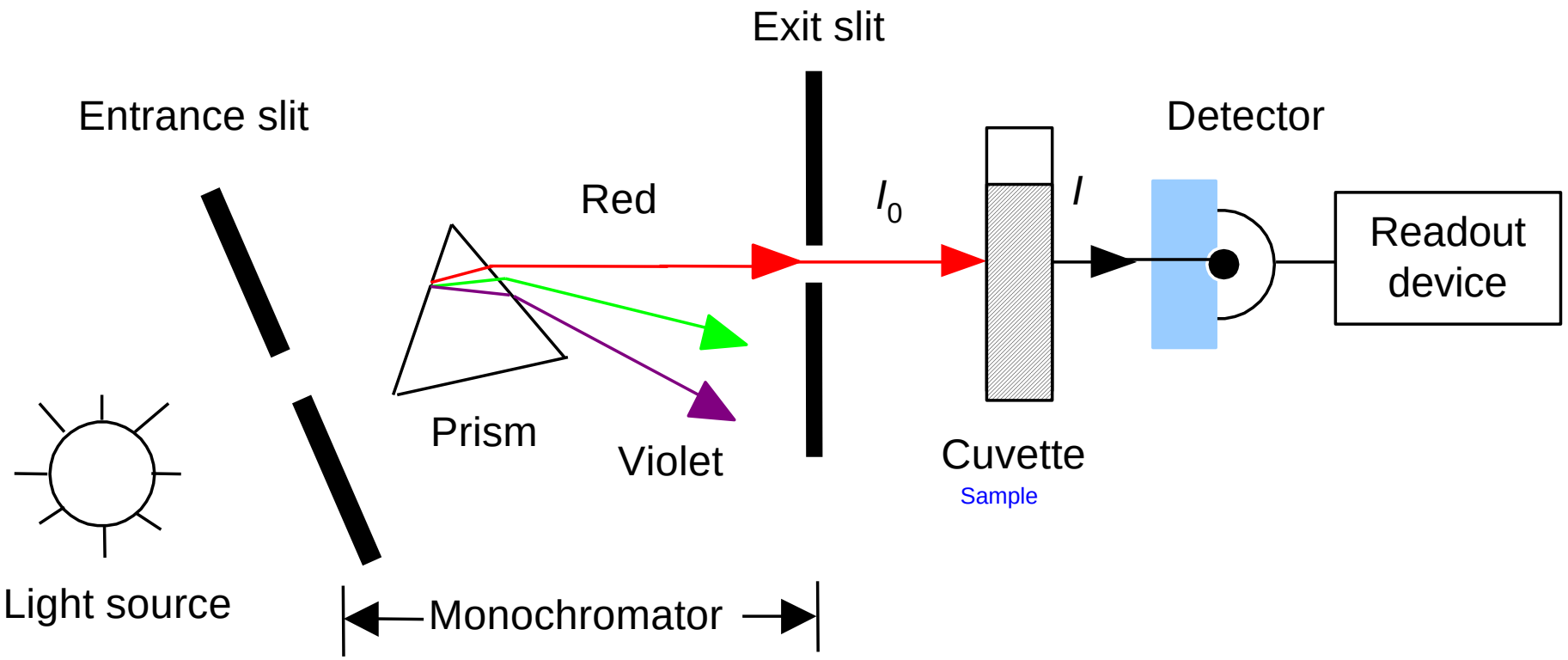
The interaction between the electromagnetic wave and the sample can be very useful to obtain very specific information about the composition of the sample



(c)

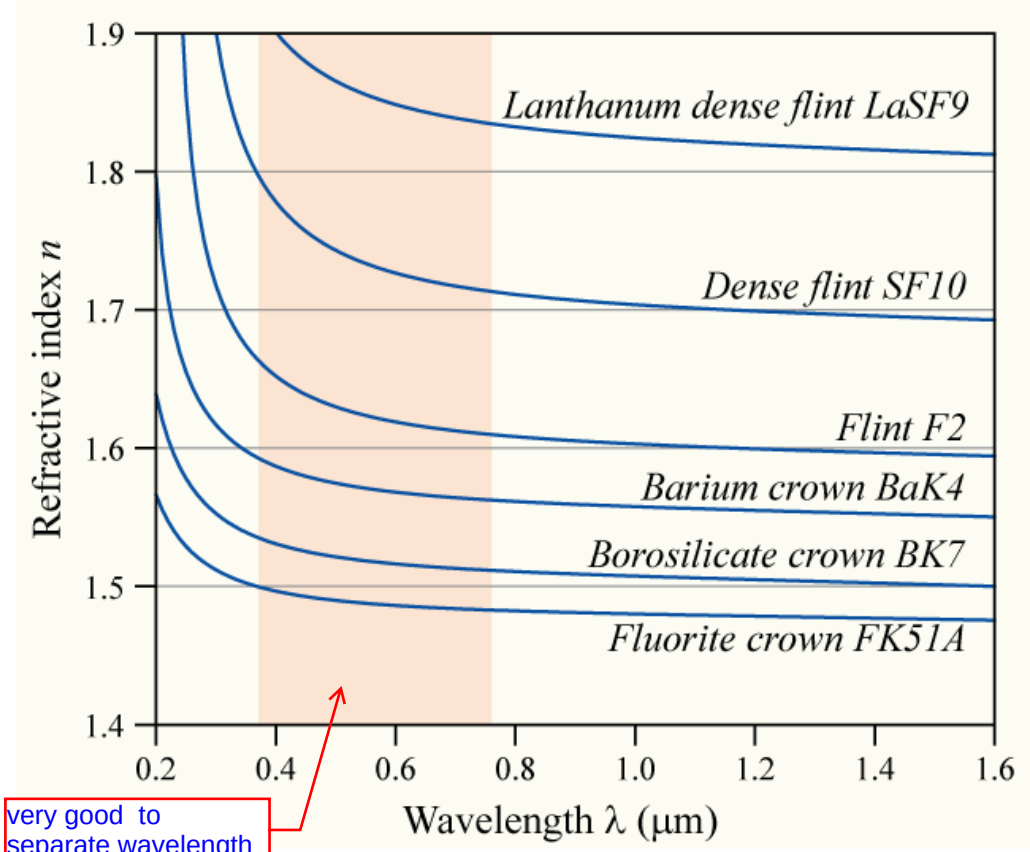
Absorption Spectrometry

We consider only one wavelenght using the monochromator from a wide source, and then we compare the "starting" I0 and transmitted I intensity to check the absorption



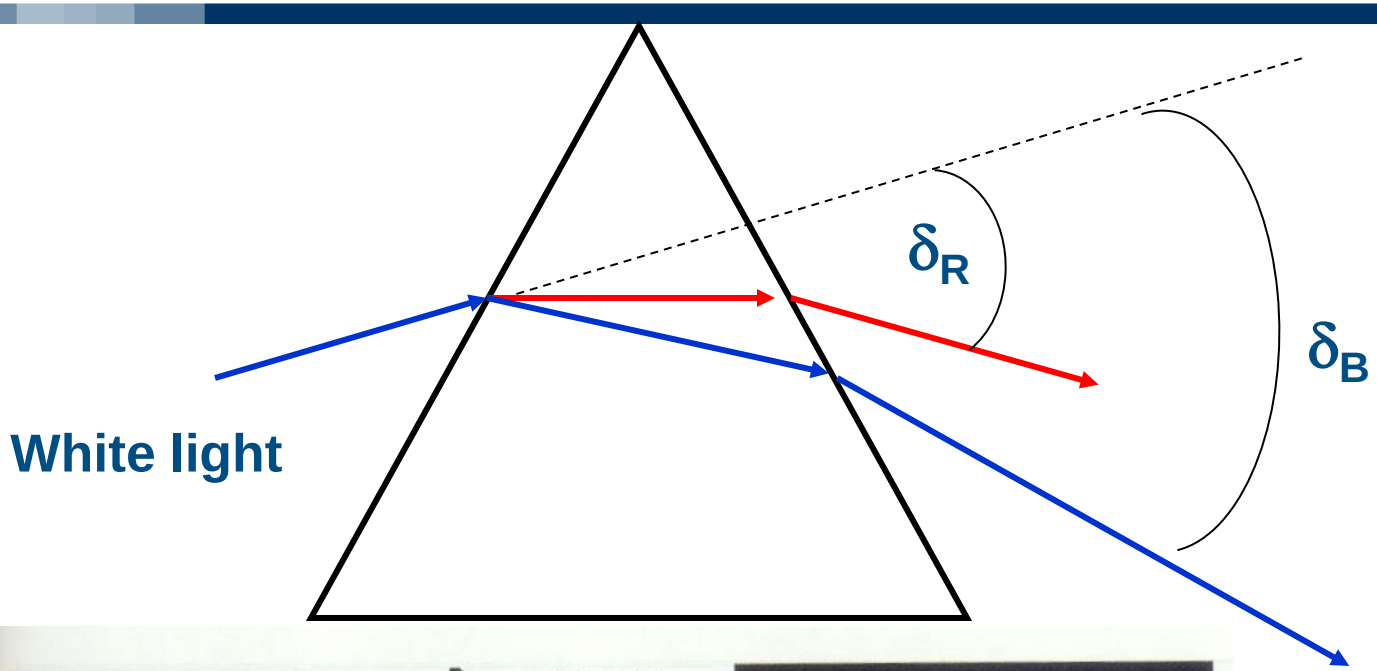
Optical dispersion

In a dispersive prism, material dispersion (a wavelength-dependent refractive index) causes different colors to refract at different angles, splitting white light into a rainbow.



variation of refractive index vs. vacuum wavelength for various glasses

Wavelength separation



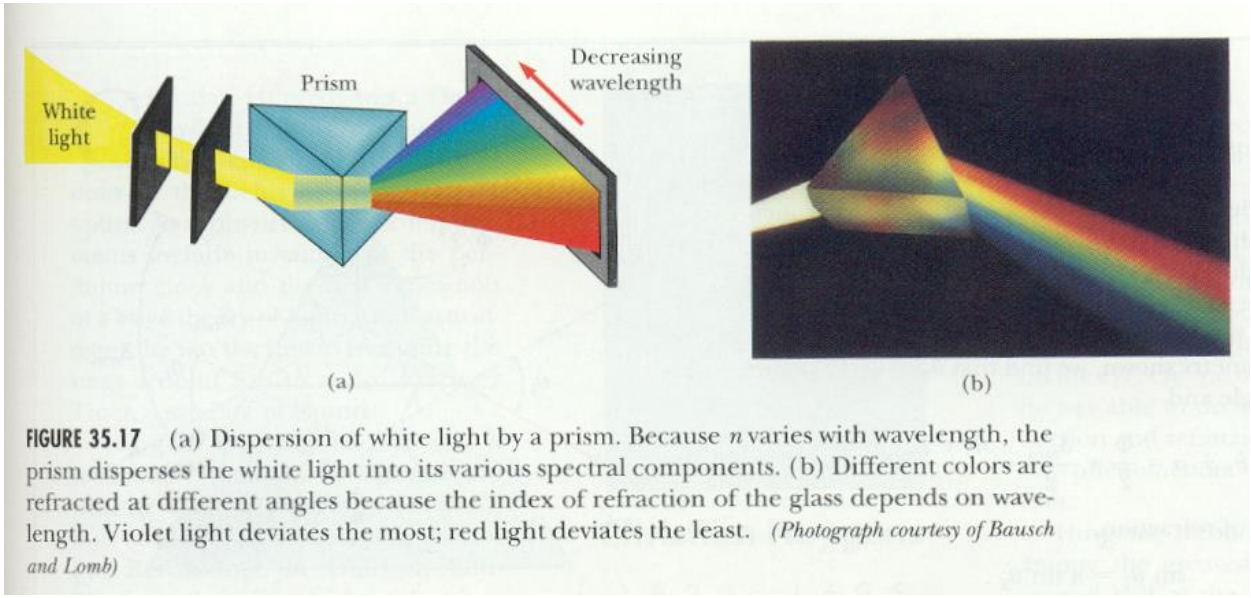
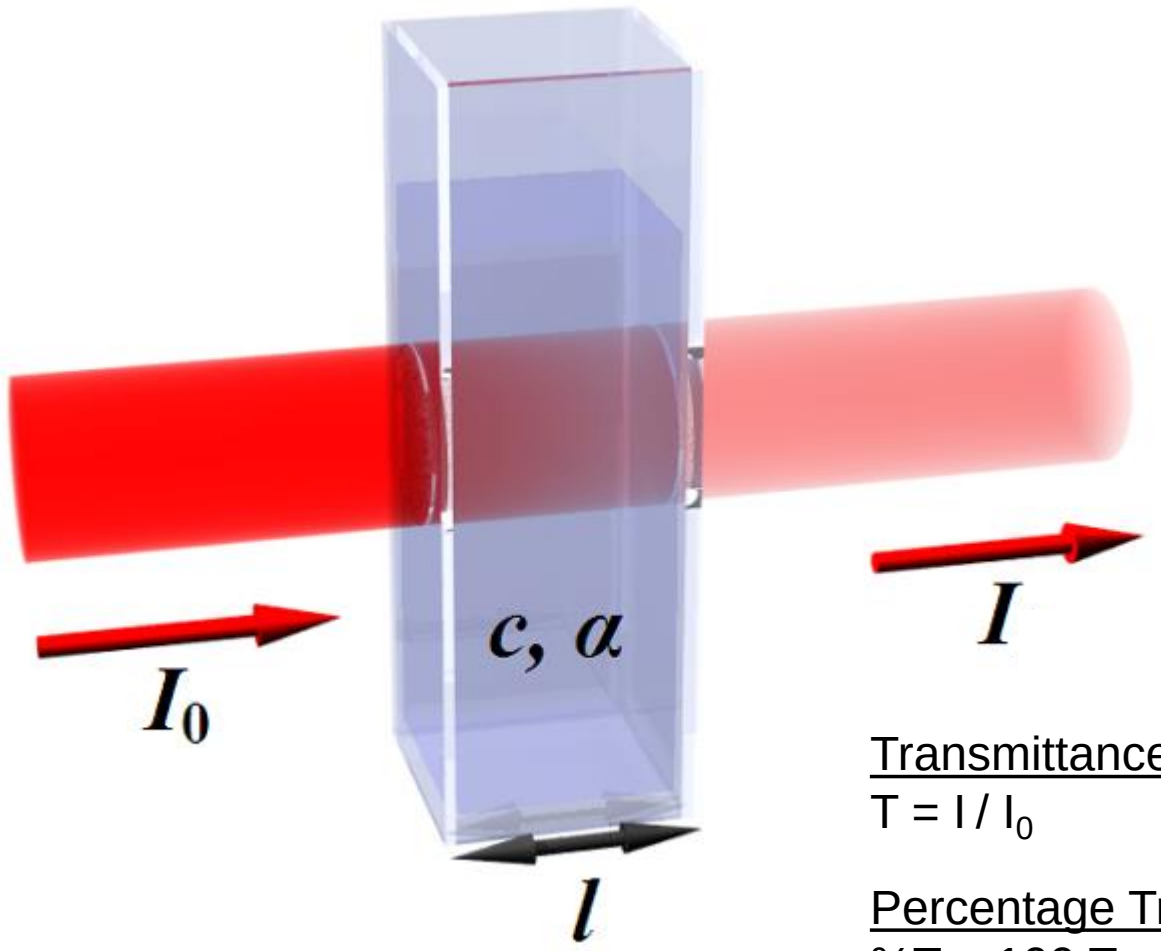


FIGURE 35.17 (a) Dispersion of white light by a prism. Because n varies with wavelength, the prism disperses the white light into its various spectral components. (b) Different colors are refracted at different angles because the index of refraction of the glass depends on wavelength. Violet light deviates the most; red light deviates the least. *(Photograph courtesy of Bausch and Lomb)*

Light transmittance



Transmittance

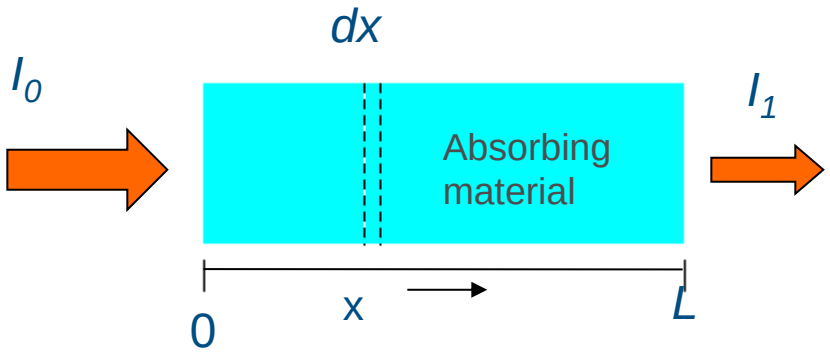
$T = I / I_0$ (Very low when the sample is very dark)

Percentage Transmittance

$\%T = 100\ T$

Lambert-Beer's law

Equal thicknesses of a given material absorb a constant fraction of light energy



L: optical path of the sample (length) [cm]

α: absorption coefficient [cm^{-1}] = h·C

h: molar extinction coefficient [L mol^{-1} cm^{-1}]

C: concentration of the substance in the sample [mol L^{-1}]

variazione di intensità lungo lo spazio ottico x

$$\frac{dI}{dx} = -\alpha I$$

$$Integrating\ by\ x\ \ from\ 0\ to\ L$$

$$\frac{dI}{I} = -\alpha\, dx$$

$$\int \frac{1}{I} dI = \int -\alpha\, dx$$

$$\ln(I) - \ln(I_0) = -\alpha L$$

$$\ln(I) = \ln(I_0) - \alpha L$$

$$I = I_0 \cdot e^{-\alpha L}$$

$$I = I_0 \cdot e^{-hCL}$$

Transmittance, absorbance nd optical density

Transmittance

$\mathbf{T = I / I_0} = e^{-hLC}$

Percentage transmittance

$\%T = 100\ T = 100 \cdot e^{-hLC}$

Absorbance

$\mathbf{A = \ln (I_0 / I)} = \ln (1 / T) = hLC$

Optical Density

Optical density (OD) is defined as absorbance with L=1 cm

High OD -> high A

$\mathbf{OD = \ln (I_0 / I_t) = hC}$

(I_0 = intensity of incident light, I_t= intensity of transmitted light)

Transmittance and absorption expressed in base 10 (optical power)

veloce

$$P = P_0 \cdot 10^{-hLC}$$

stessa cosa, invece che intensità la potenza

P_0= incident radiant optical power

P= output power

L: optical path of the sample (length) [cm]

α: absorption coefficient [cm^{-1}]

C: concentration of the substance in the solution [mol L^{-1}]

$$\%T = 100\, P/P_0 = (100) \cdot 10^{-hLC}$$

Transmittance and absorption expressed in base 10 (optical power)

Transmittance

$T = P/P_0 = 10^{-hLC}$

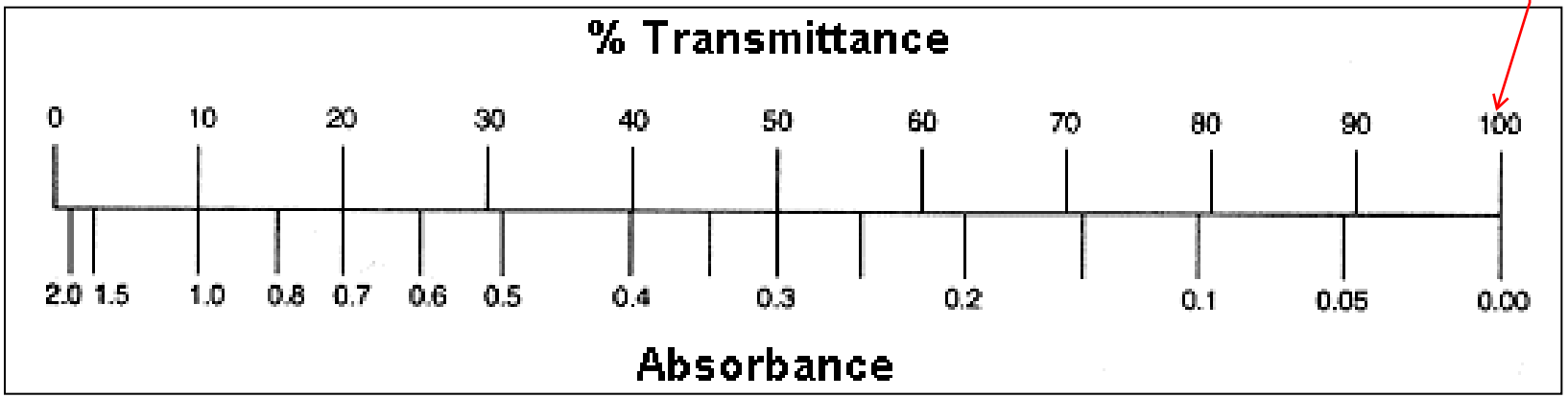
Percentage Transmittance

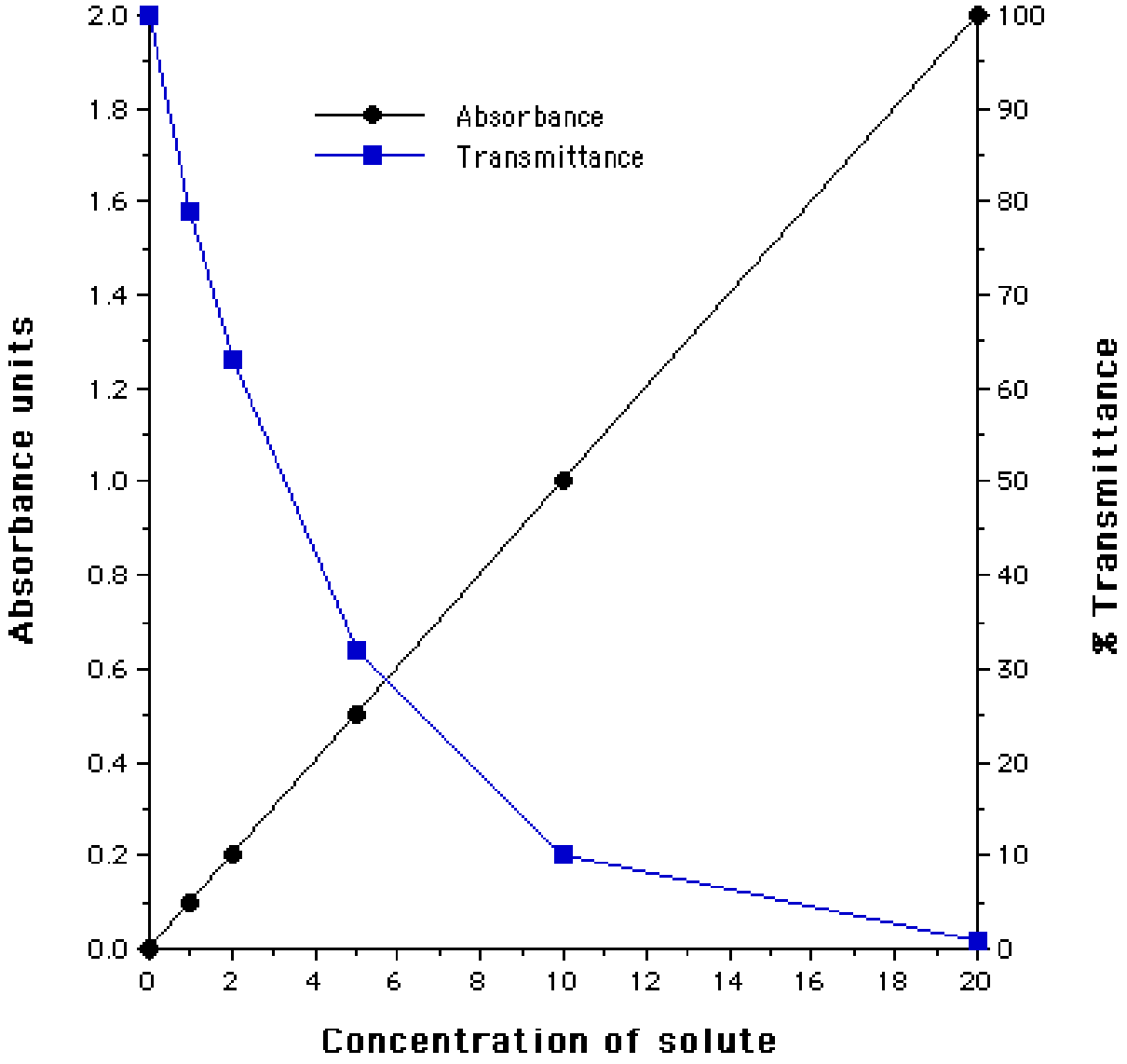
$\%T = 100\ T = 100\ P/P_0 = 100 \cdot 10^{-hLC}$

Absorbance

$A = \log (P_0 / P) = \log (1 / T) = hLC$

$A = \log (100 / \%T) = 2 - \log \%T$



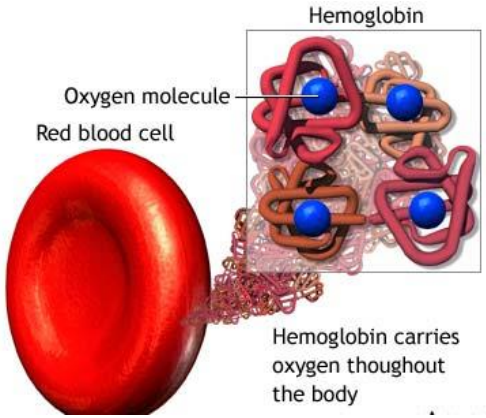

Absorbance
Transmittance
Absorbance units
% Transmittance
Concentration of solute
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20

veloce

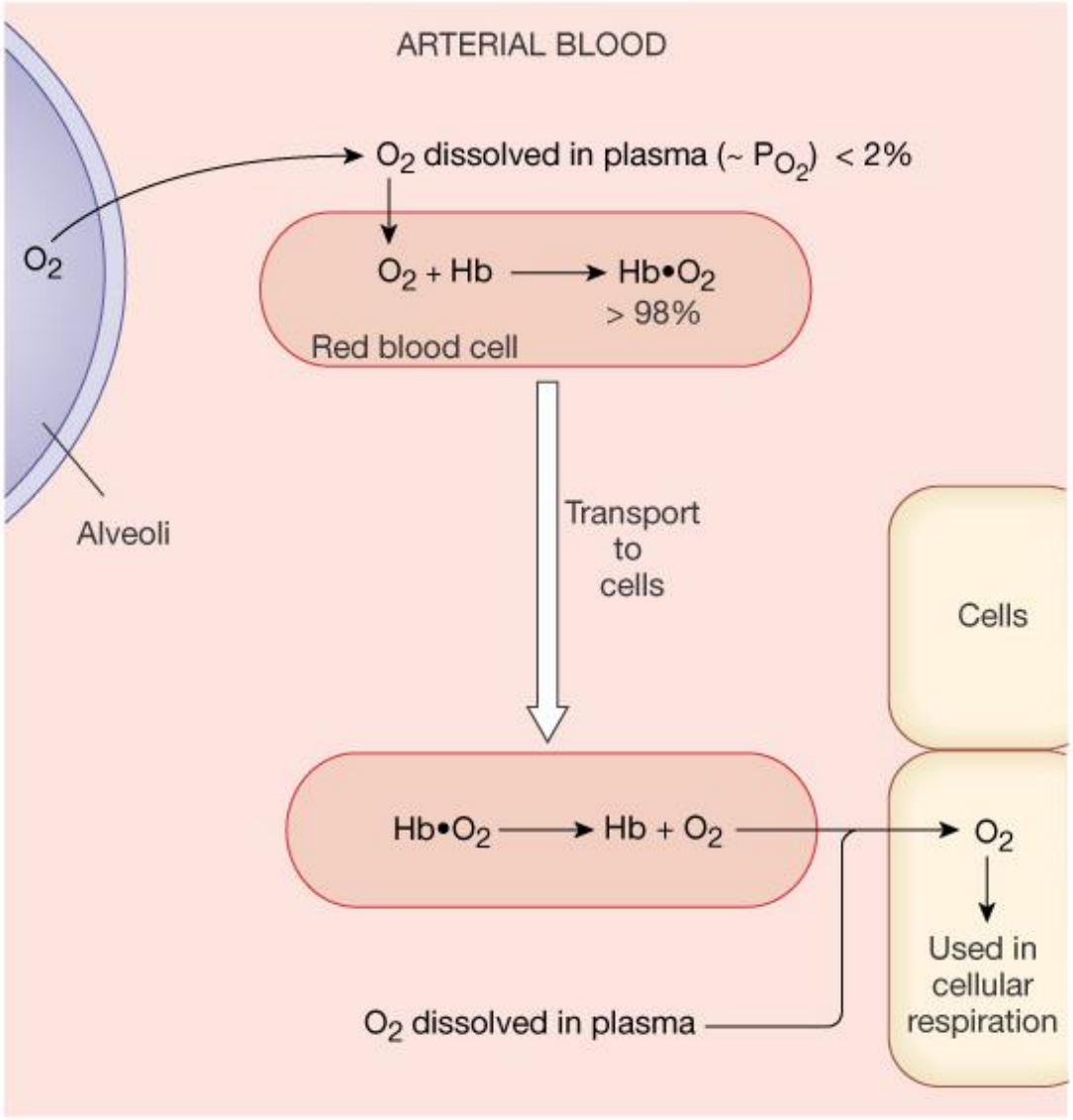
Gas Transport in the Blood: Oxygen

veloce

- 98% Bound to hemoglobin (Hb)
- 2% Dissolved in plasma
  - Proportional to partial pressure of O_2
  - 0.003 ml O_2/100 ml blood



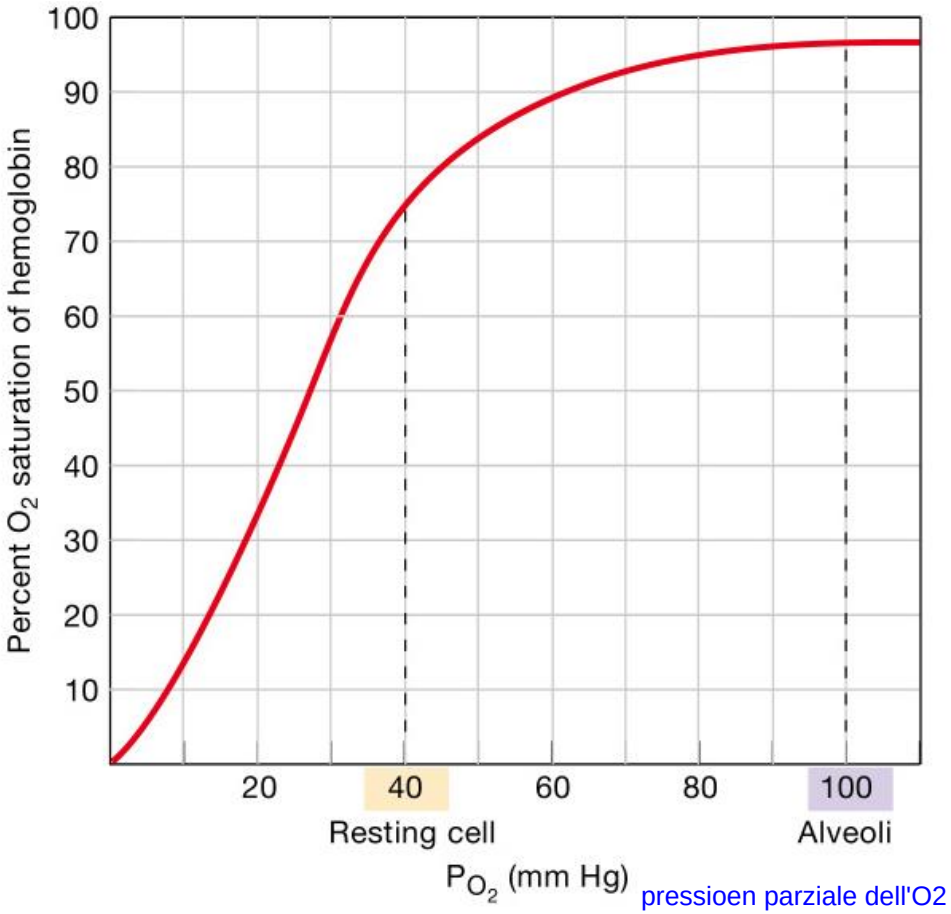
4 binding sites per Hb molecule



Oxygen Saturation and disassociation Curve

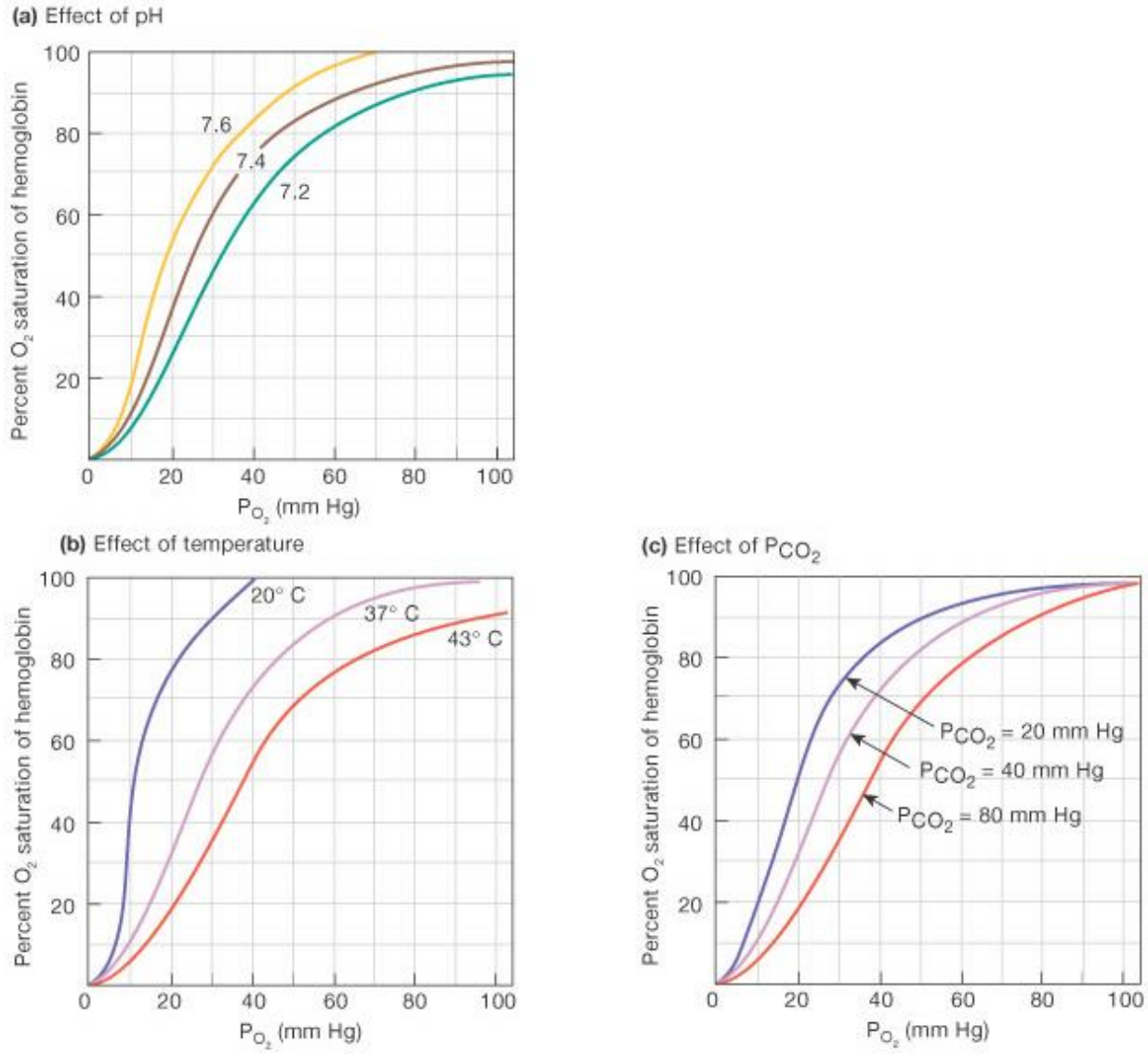
oxigenated hemoglobine

$$SO_2(\%) = \frac{HbO_2}{Hb + HbO_2} * 100$$



(In arterial blood SaO_2 ~ 98%
In venous blood, SvO_2 ~ 75%)

Factors that Modify Hb Transport of Oxygen



Typical Arterial Blood Oxygen Content

PaO_2=100 mm Hg; SaO_2=97%; [Hb]=15 mg/dL

1.34 mL O_2 /g Hb = O_2 capacity =Hb_s

Dissolved O_2

$Cd,O_2 = aO_2 \cdot PO_2 = 0.0031 \cdot 100 =$ **0.31 mL/dL**

Bound O_2

$Cb,O_2 = SaO_2 \cdot [Hb] \cdot Hb_s = 0.97 \cdot 15 \cdot 1.36 =$ **19.79 mL/dL**

Total O_2 content

$Cd,O_2 + Cb,O_2 = 0.31 + 19.79 =$ **20.1 mL/dL**

Determinants of Oxygen Delivery and Consumption

no

Oxygen Delivery

$DO_2 = CO \times Hb \times 1.34 \times SaO_2$

Oxygen Consumption

$V'O_2 = CO \times Hb \times 1.34 \times (SaO_2 - SvO_2)$

CO: Cardiac Output
Hb: Haemoglobin
SaO_2: Arterial Oxygen Saturation
SvO_2: Mixed Venous Oxygen Saturation
DO_2: Delivery
VO_2: Consumption

Monitoring of blood gases

Monitoring of blood gases is fundamental in intensive care and during surgical interventions.
pO_2, pCO_2 e pH provide information on respiratory/metabolic equilibrium, on the adequacy of blood oxygenation and CO_2 removal.

⇒ This information is needed to intervene by varying the setting of mechanical ventilation, the composition of ventilatory gases or the pharmacological treatment of the patient.

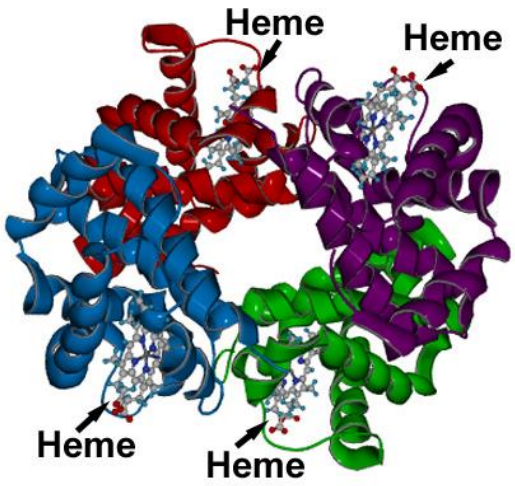
Possibilities for blood gas monitoring:
1) Blood sampling and analysis through a blood gas analyzer ("one-shot" measurement);
2) Continuous monitoring
- *in vivo (intravascular)*
  - invasive
  - noninvasive
- *ex vivo (extravascular)*

Specifications for blood gas sensors

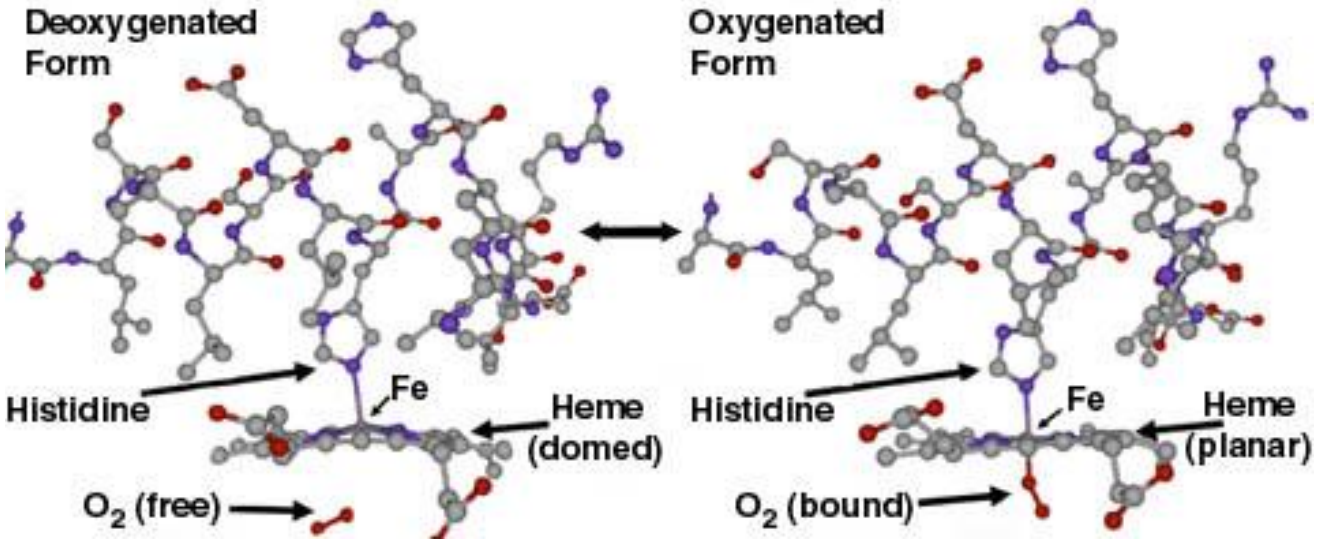
fast

	pO_2	pH	pCO_2
Measurement Range	4-80 kPa (30-600 mmHg) fornito O2 puro al paziente	6.8-7.8	2.7-13.3 kPa (20-100 mmHg)
Resolution	0.133 kPa (4-20) (1 mmHg) 0.667 kPa (20-40) (5 mmHg) 1.333 kPa (40-80) (10 mmHg)	0.01	0.133 kPa (1 mmHg)
Temperature Range	20-40°C	20-40°C	20-40°C
Stability (/72 hours)	<1.066 kPa	<0.03	<0.8 kPa
Response Time	<3 min	<3 min	<3 min
Insensivity for	Anesthetic gases, pH, pCO_2	Anesthetic gases, pO_2, pCO_2	Anesthetic gases, pH, pO_2

Deoxygenated/ oxygenated hemoglobin



molecular model of hemoglobin

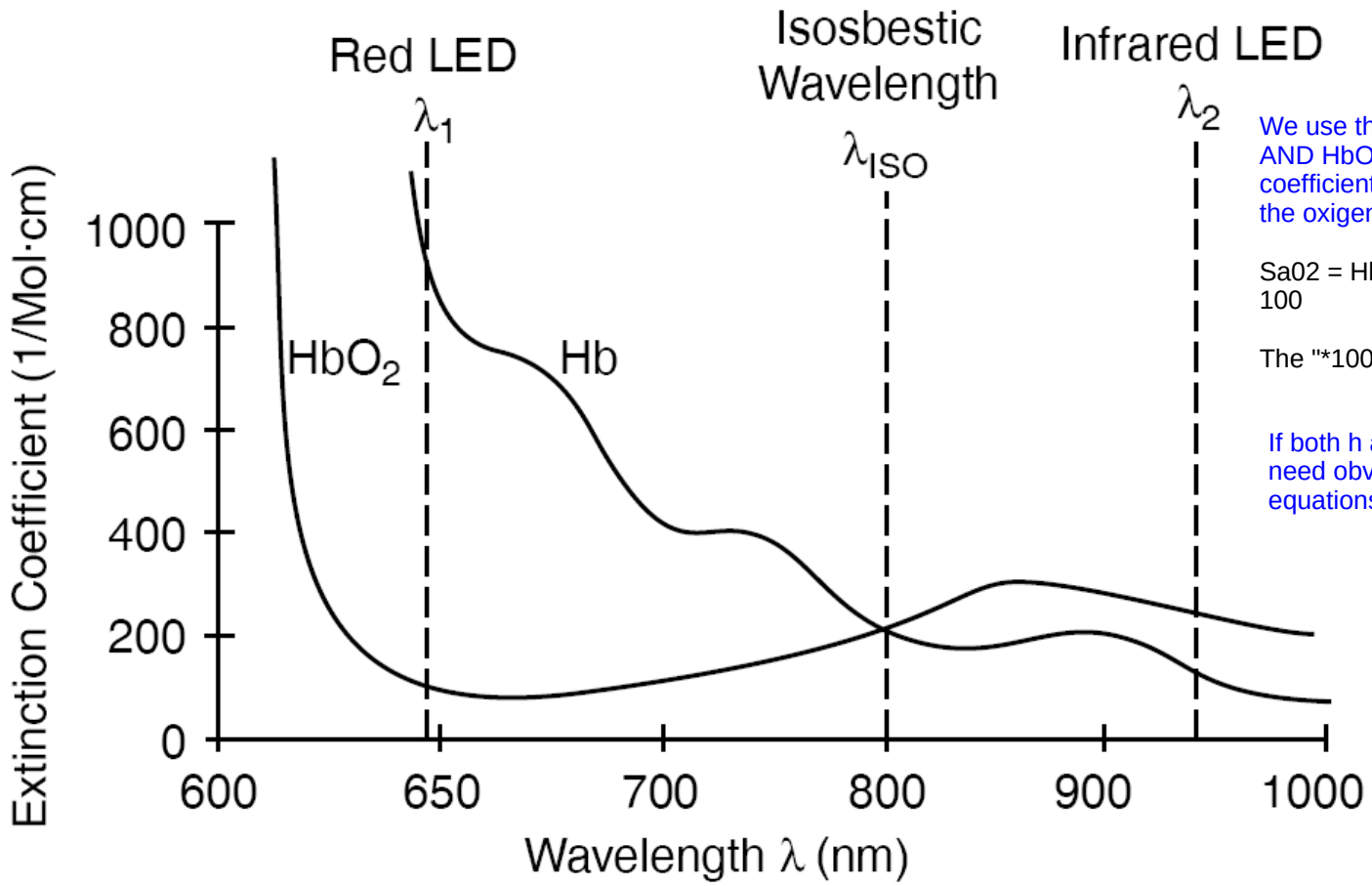


L'heme è un coso che è presente nell... emo globina (è l'emo)

The heme group and a portion of the hemoglobin protein that is directly attached to the heme.

When hemoglobin is deoxygenated (left), the heme group adopts a domed configuration. When hemoglobin is oxygenated (right), the heme group adopts a planar configuration. As shown in the figure, the conformational change in the heme group causes the protein to change its conformation and **its optical properties** as well.

Optical Oximetry (measurement of blood oxygen saturation)



We use the fact that the two Hb AND HbO2 have different coefficient, so that we can get the oxigen saturation with:

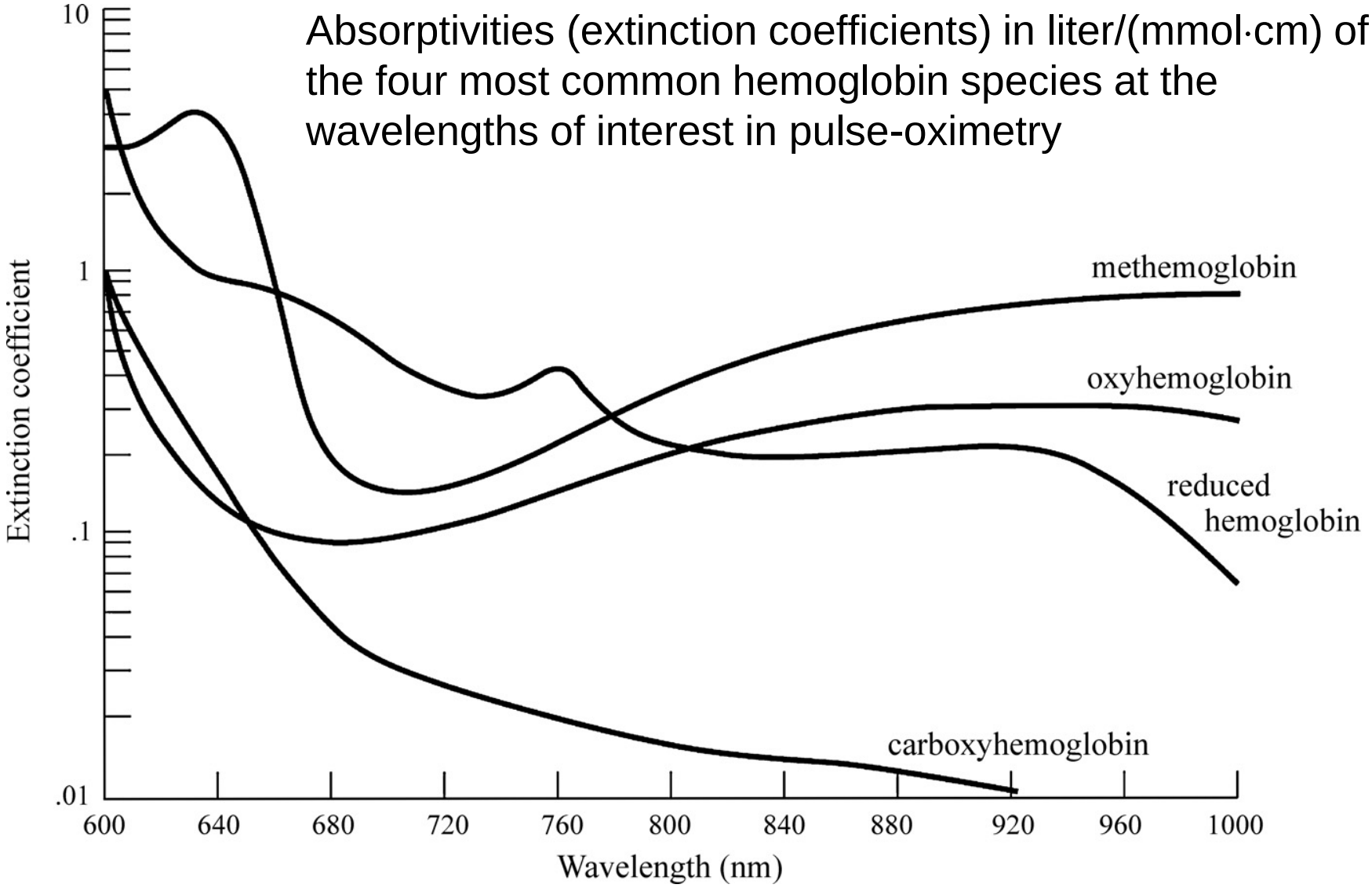
Sa02 = HbO2 / (HbO2 + Hb) * 100

The "*100" gives the percentage

If both h and C are unkown we need obv. to write two equations

Figure 10. Light absorption spectra of oxygenated and deoxygenated hemoglobin.

Absorptivities (extinction coefficients) in liter/(mmol·cm) of the four most common hemoglobin species at the wavelengths of interest in pulse-oximetry



Optical Oximetry (measurement of blood oxygen saturation)

Devices for optical oximetry measure oxygen saturation in the blood or in tissues by evaluating the difference of absorption spectra of organic compounds that carry oxygen, like hemoglobin (Hb).

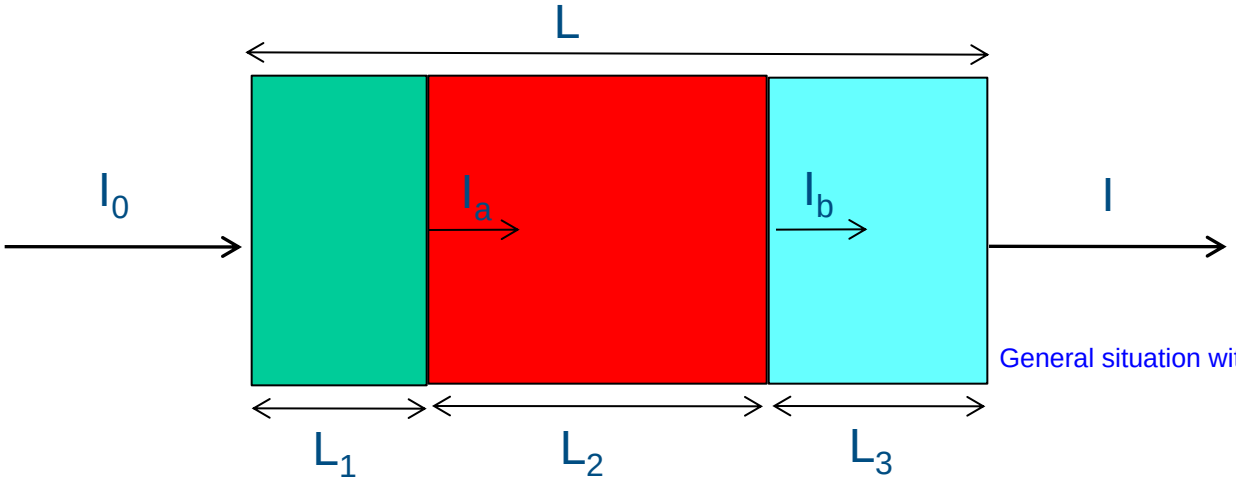
In this case the “dye” (indicator) is inside the solution under exam (blood).

The measurement principle of optical oximeters is based on the different absorption spectra of Hb and HbO_2 (this is also the reason why venous and arterial blood have different colors).

At least two wavelengths are utilized, one red (around 660 nm) and the other infrared (between 805 and 1000 nm).

The absorption coefficient of Hb and HbO_2 is the same at 805 nm, and this wavelength, called “isobestic”, is used as a reference.

Beer's Law in multiple absorbers



General situation with 3 unknowns

$$I_a = I_0 \cdot e^{-h_1 C_1 L_1}$$

$$I_b = I_a \cdot e^{-h_2 C_2 L_2} = I_0 \cdot e^{-h_1 C_1 L_1} \cdot e^{-h_2 C_2 L_2}$$

$$I = I_b \cdot e^{-h_3 C_3 L_3} = I_0 \cdot e^{-h_1 C_1 L_1} \cdot e^{-h_2 C_2 L_2} \cdot e^{-h_3 C_3 L_3}$$

$$I = I_0 \cdot e^{-(h_1 C_1 L_1 + h_2 C_2 L_2 + h_3 C_3 L_3)}$$

total absorbance

$$A_t = \ln \frac{I_0}{I} = \ln \left[e^{(h_1 C_1 L_1 + h_2 C_2 L_2 + h_3 C_3 L_3)} \right]$$

C1L1 are not known!

total absorbance: sum of each assorbance

$$= h_1 C_1 L_1 + h_2 C_2 L_2 + h_3 C_3 L_3 = A_1 + A_2 + A_3$$

Transmission oximetry

By defining absorbance as $A = \ln (I_0 / I_t) = hLC$
(I_0 = intensity of incident light, I_t= intensity of transmitted light) and applying Beer's law to the sample we have:

$$A = ln(I_0 / I_t) = L\left[h(Hb)\cdot C(Hb) + h(HbO_2)\cdot C(HbO_2)\right]$$

We can consider the case where L is the same for the three paths, we have a linear contribution overall done by the three

C = concentration
h = extinction coefficient (absorbance)
L = optical path

⇒ **Linear contribution of the different components to the overall absorption**

Transmission oximetry

so that we have 2 equations with 2 unknowns

By measuring absorbance A at two different wavelengths (λ_1 and λ_2), the concentrations of hemoglobin and oxi-hemoglobin (C(Hb) and C(HbO_2), respectively) can be determined as unknowns of a two-equation linear system, in which extinction coefficients at the different wavelengths (h(λ_1,HbO_2), h(λ_2,HbO_2), h(λ_1,Hb), h(λ_2,Hb)) are known.

value of the exct. coefficient for lambda1 for HbO2

Transmission oximetry

unknown 1

$$C(Hb) = \frac{\left[h(\lambda_{2,Hb}) \cdot A(\lambda_1) - h(\lambda_{1,Hb}) \cdot A(\lambda_2)\right]}{L} \cdot \left[h(\lambda_{1,HbO2}) \cdot h(\lambda_{2,Hb}) - h(\lambda_{2,HbO2}) \cdot h(\lambda_{1,Hb})\right]$$

unknown 2

$$C(HbO_2) = \frac{\left[h(\lambda_{2,HbO2}) \cdot A(\lambda_1) - h(\lambda_{1,HbO2}) \cdot A(\lambda_2)\right]}{L} \cdot \left[h(\lambda_{1,Hb}) \cdot h(\lambda_{2,HbO2}) - h(\lambda_{2,Hb}) \cdot h(\lambda_{1,HbO2})\right]$$

Oxygen saturation is obtained (without knowing L) as:

$$SO_2 = \frac{C(HbO_2)}{C(Hb) + C(HbO_2)}$$ (beacause L gets simplified)

Reflection/transmission oximetry

We measure the back reflected light (backscattering), sampled at 2 different wavelenghts

In **reflection oximetry**, the back-reflected light from the sample ("backscattering") is sampled at two different wavelengths (λ_1 and λ_2) and oxygen saturation is estimated from the following empirical equation:

$$SO_2 = A - B \cdot \frac{R(\lambda_1)}{R(\lambda_2)}$$

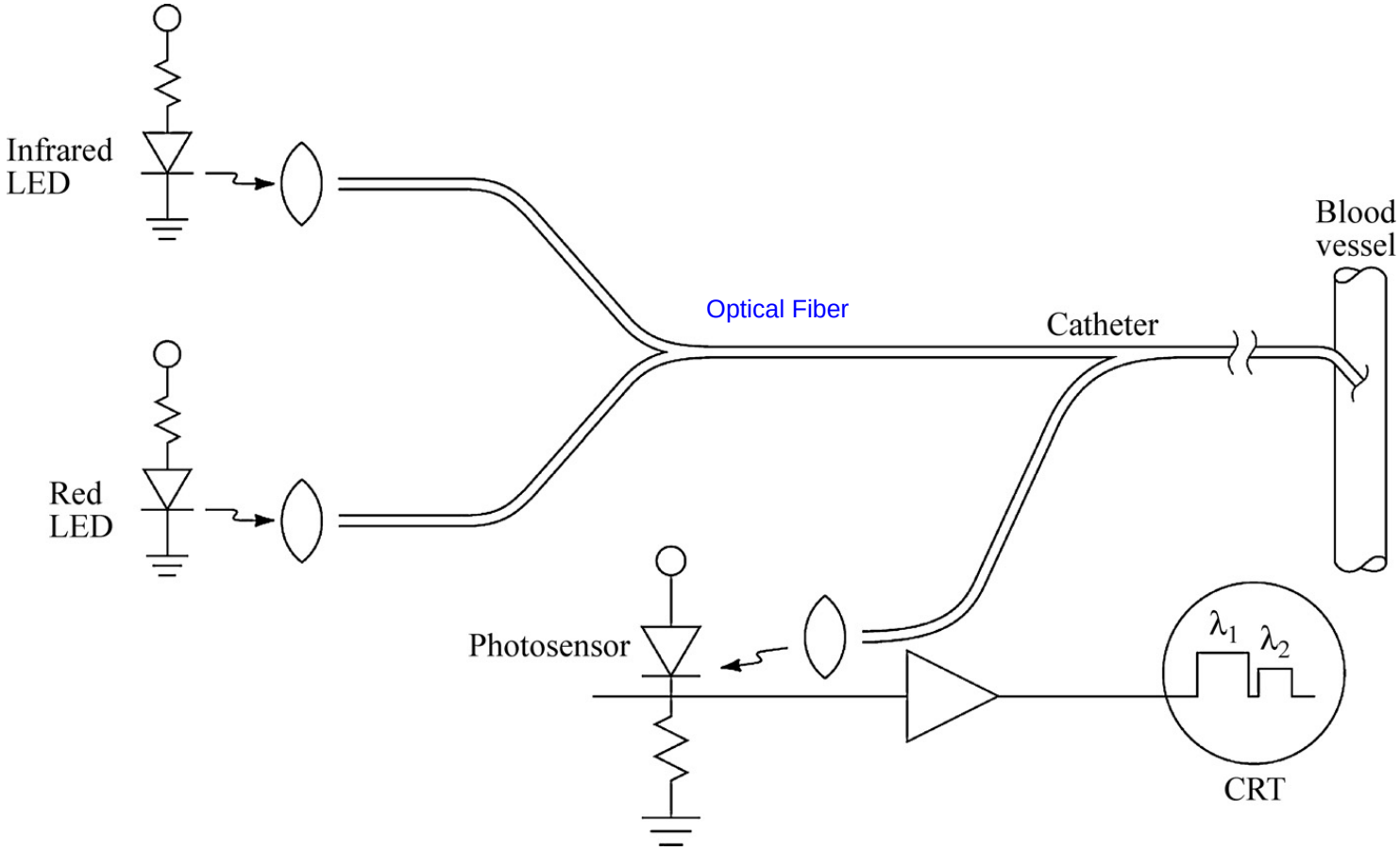
Ofc. the reflected portion of reflected light depends on the absorbed! The amount that the sensor sense it's lower than in the trans. oximetry

where $R = \ln (I_0 / I_r)$

reflectance (I_0 = intensity of incident light, I_r= intensity of reflected light)
A and B = constants that depend on the hematocrit (amount of red blood cells in blood volume). In order to compensate this dependency, sometime a third wavelength is used.

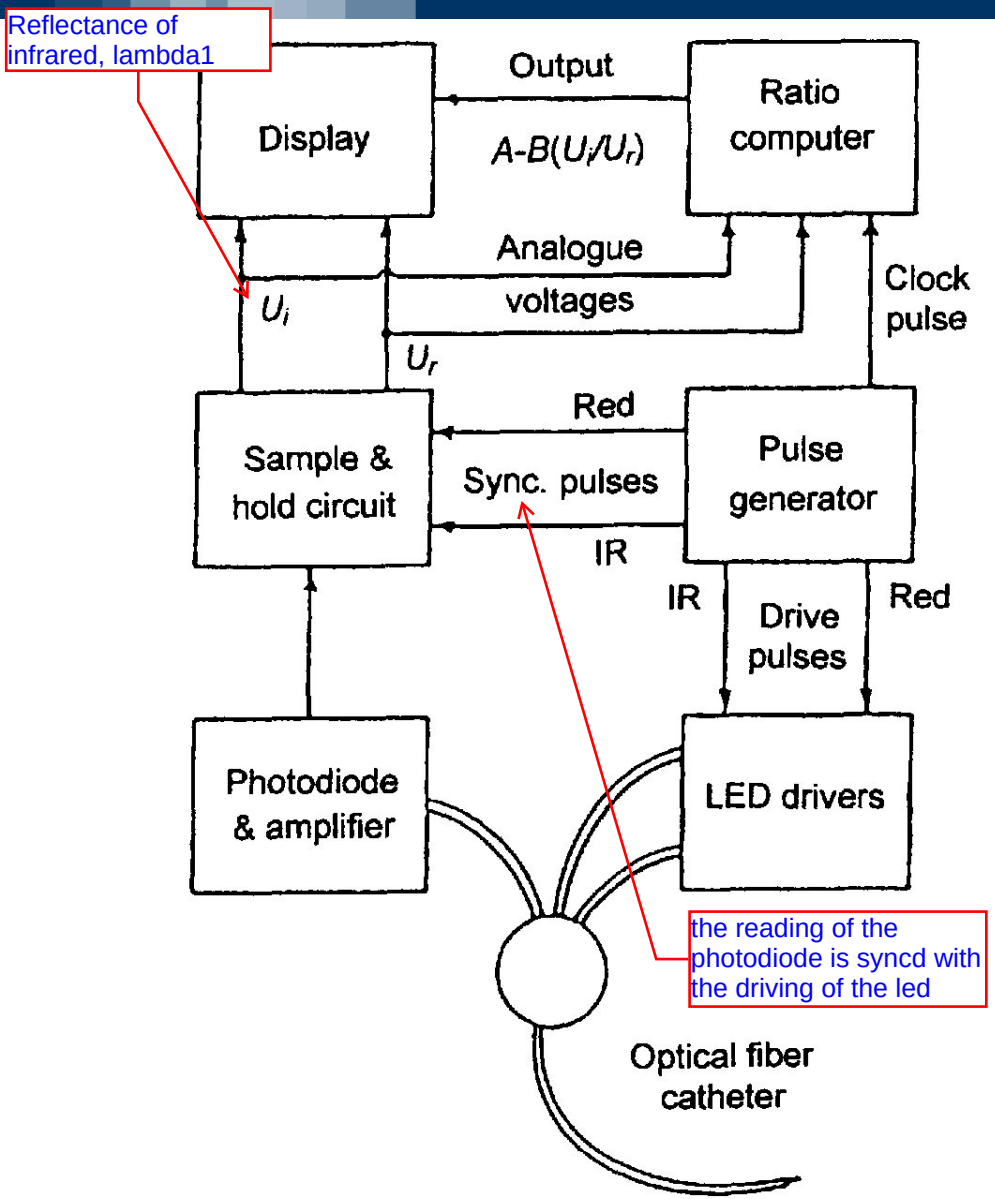
In **transmission oximetry** the light that passes through the sample is instead analyzed .

Reflection oximetry (invasive)



The oximeter catheter system measures oxygen saturation in vivo, using red and infrared light-emitting diodes (LEDs) and a photosensor. The red and infrared LEDs are alternately pulsed in order to use a single photosensor

Reflection oximetry (invasive)



It implements the empirical equation :

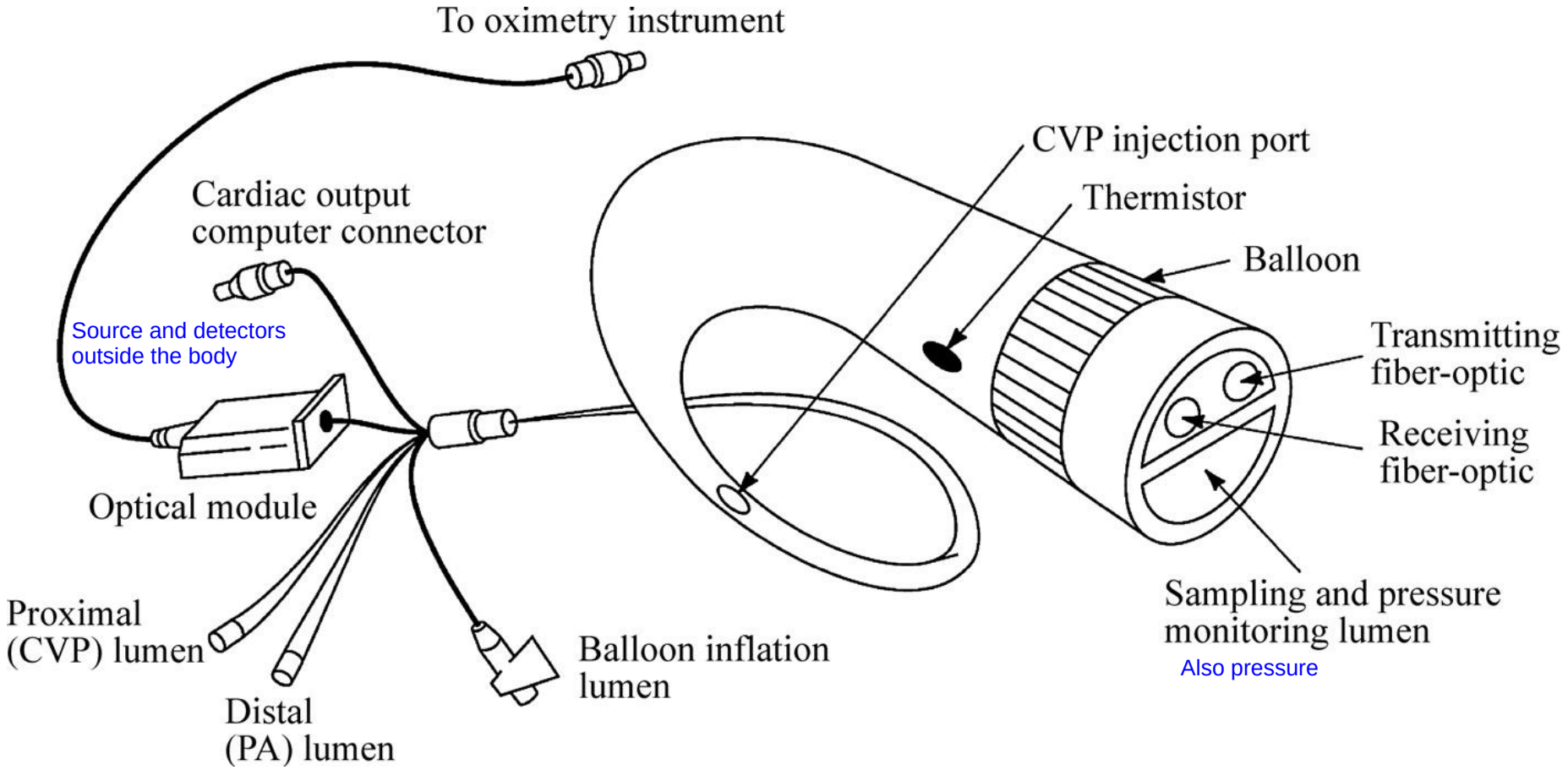
$$SO_2 = A - B \cdot \frac{R(\lambda_1)}{R(\lambda_2)} = A - B \cdot \frac{U_i}{U_r}$$

(clock frequency = 200 Hz
accuracy ≈ 1%)

We know how much IR generated light, we measure the light arriving, we calcolate the ratio, then we are able to calculate Ui. In the following pulse we do the same for the red light. Because we have PREVIOUSLY calibrated the system (A and B consntant) we can calculate the saturation. The calculation is done by the Ratio computer (just a uP, you can do with an arduino).

Clock freq. 200Hz: it means that the the switching on/Off is required no more than 5ms (LOL?)

Example:
Abbott Opticath Oximetry System

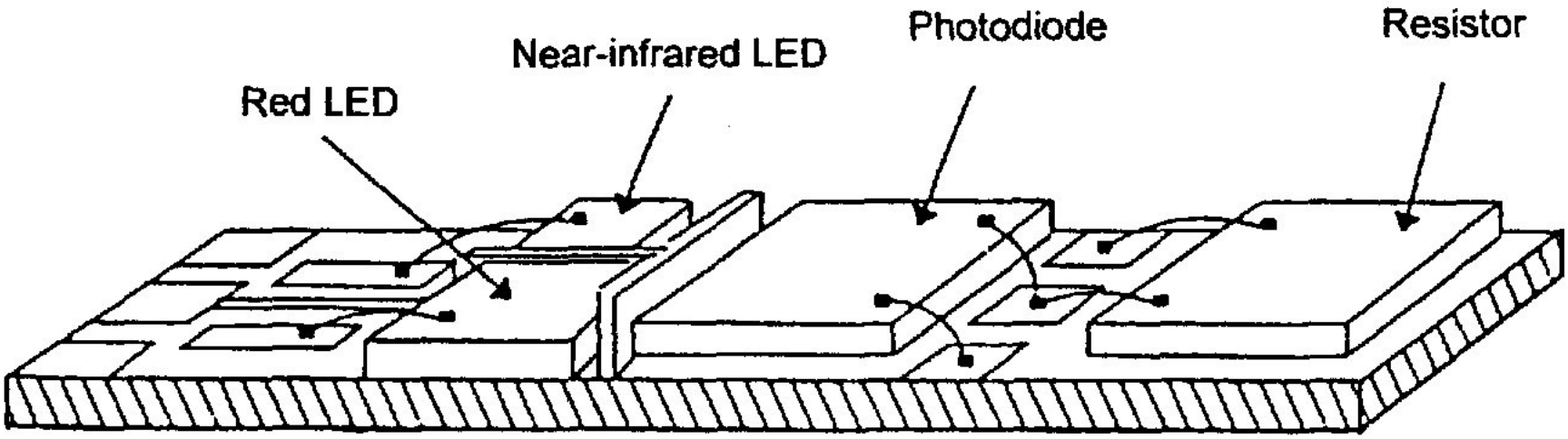


The catheter used with the Abbott Opticath Oximetry System transmits light to the blood through a transmitting optical fiber and returns the reflected light through a receiving optical fiber. The catheter is optically connected to the oximetry processor through the optical module.

Miniaturized hybrid light sources/sensors

IT'S FALSE!!!!

One of the problems in fiber optic oximeters is that damage to optical fibers results in severe measurement error. In order to overcome this problem catheter tip type oximeters using **hybrid type miniature sensors** have also been developed.



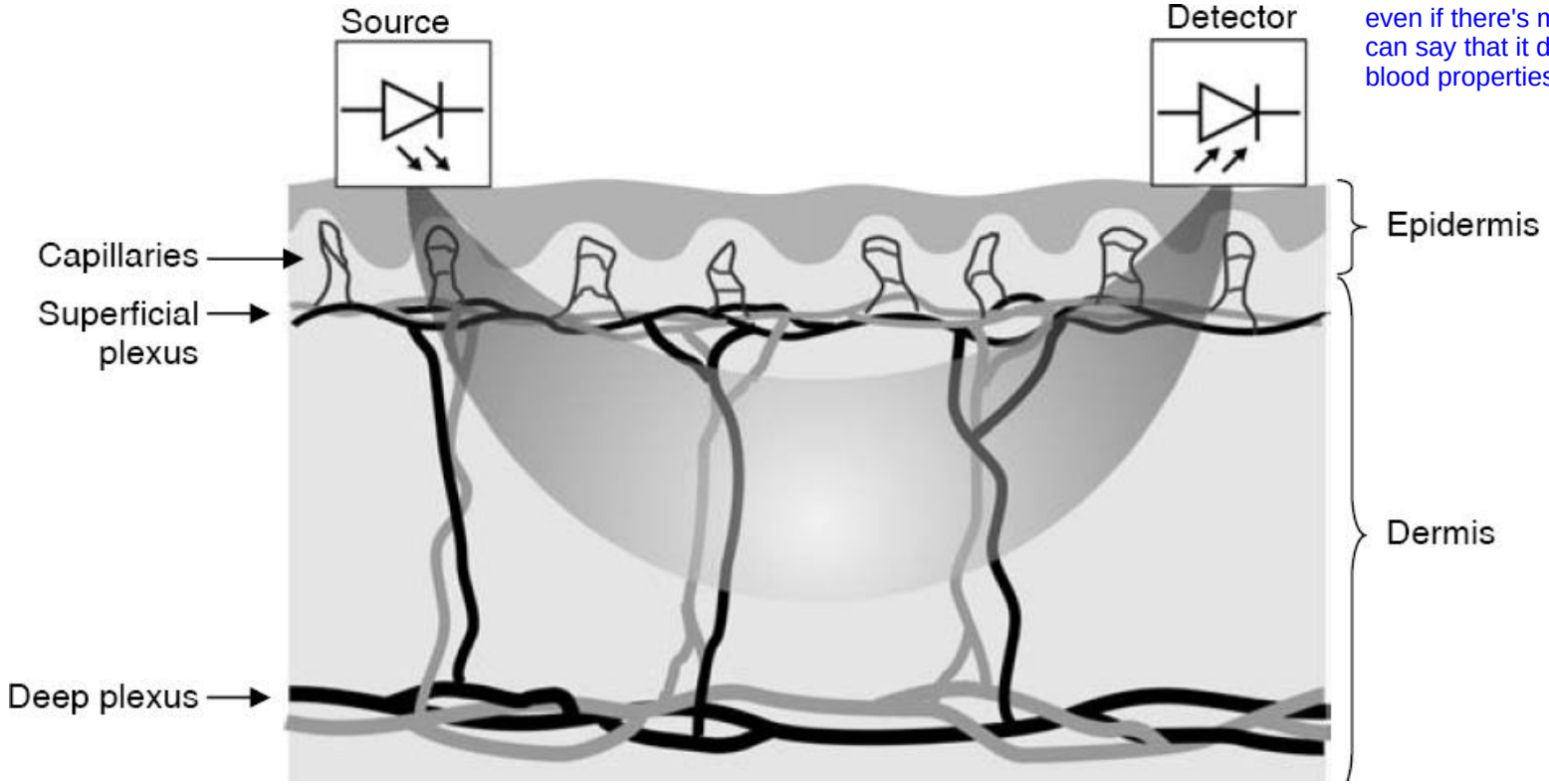
They also tried to bring the sensors/source at the end of the cateter (obv. using also wires etc.) in a MEMS, but it was abandoned. So instead of optical fibers wires are used.

Noninvasive oximetry

Problem of invasive oximetry: risks related to catheterization ⇒ development of noninvasive methods

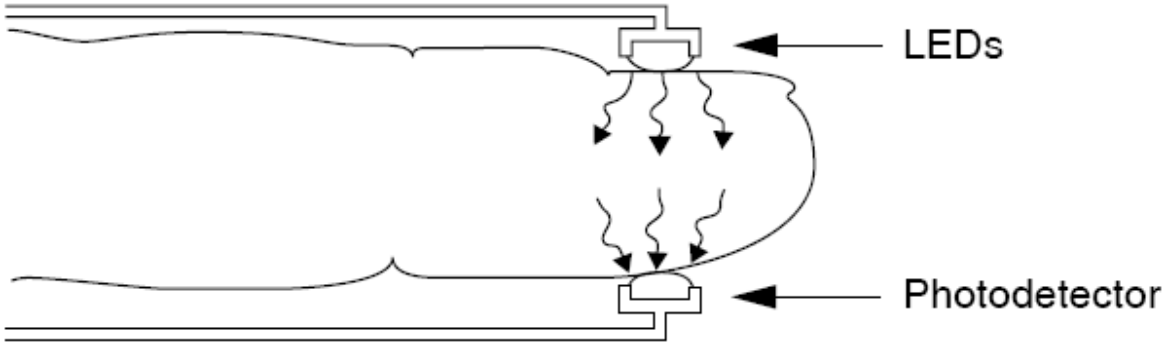
Noninvasive oximetry = tissue oximetry

(tissue = complex medium in which are distributed in an inhomogeneous way both arterial and venous vessels).

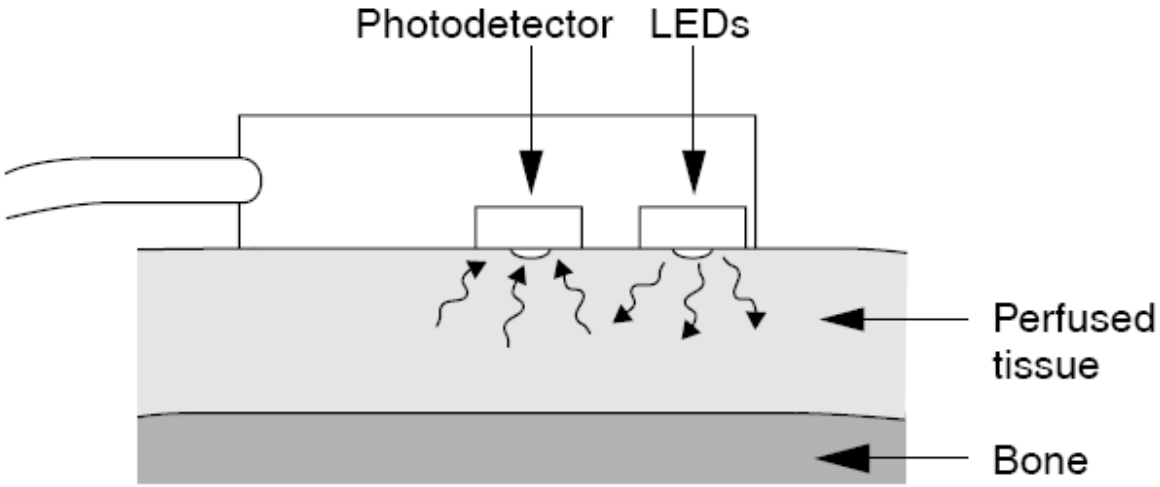


even if there's more caos we can say that it depends on the blood properties

Reflection / transmission noninvasive oximetry



Transmission sensor



Reflectance sensor

LED drive circuits

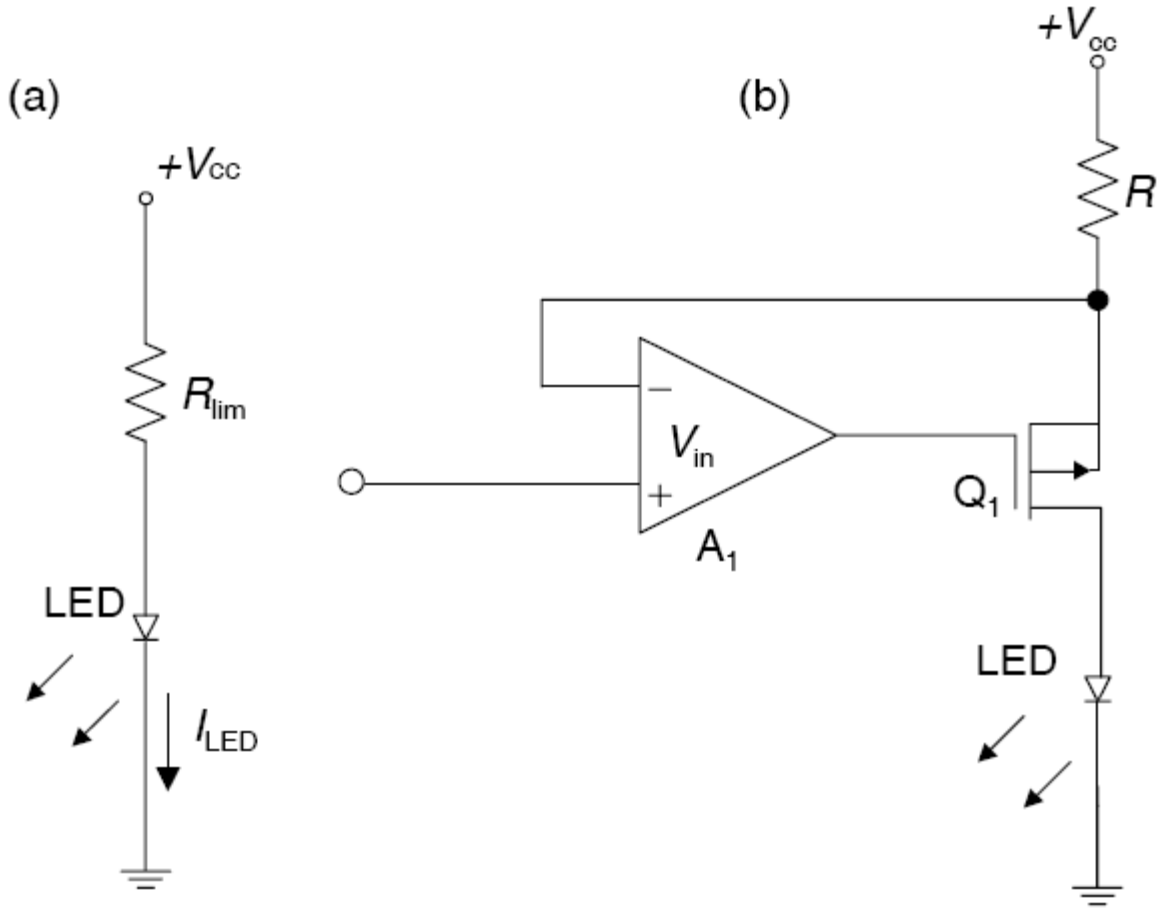
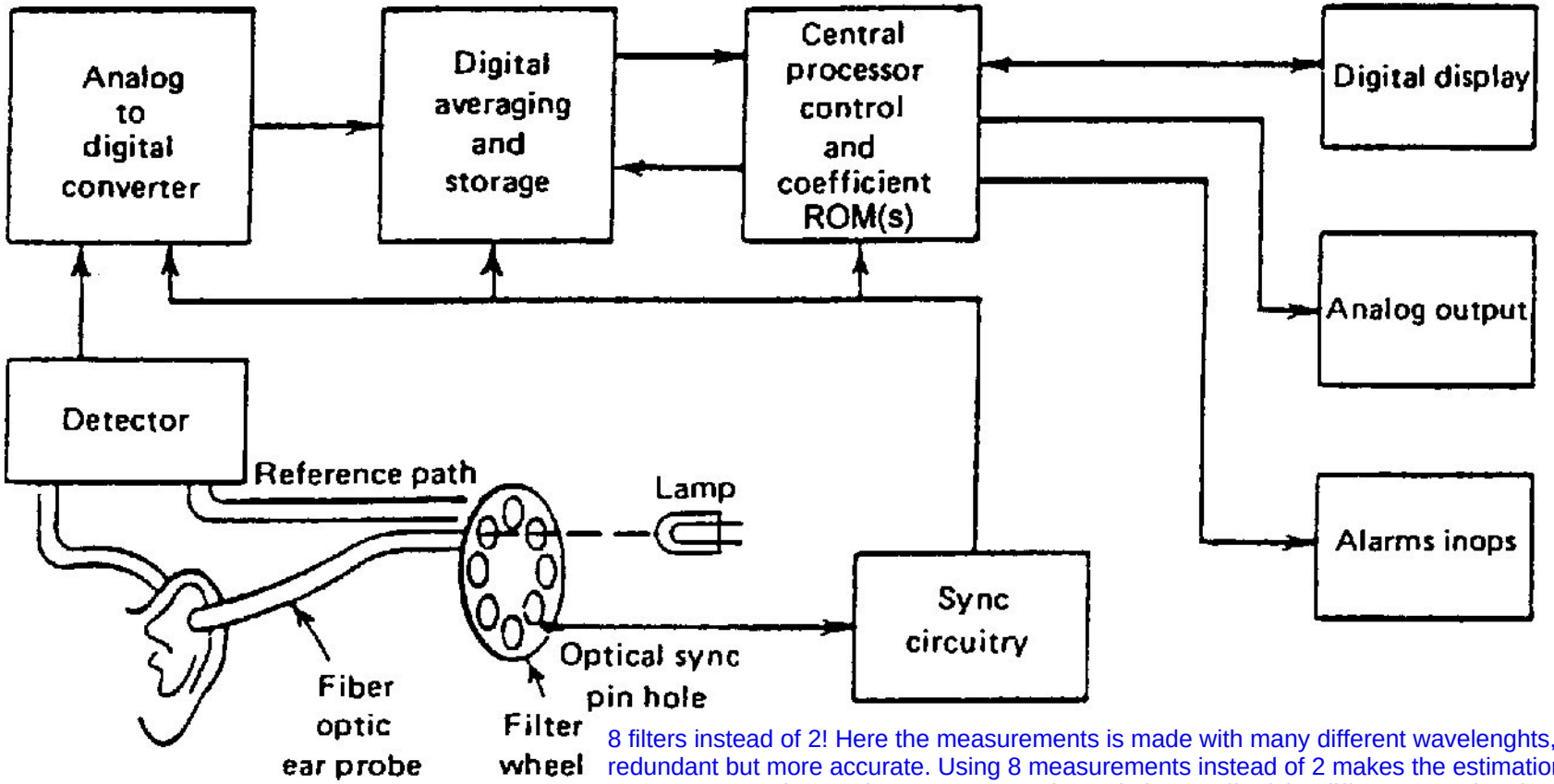


Figure 6. LED drive circuits. (a) Simple current limiting resistor. (b) Voltage controlled current source.

Noninvasive oximeter



8 filters instead of 2! Here the measurements is made with many different wavelenghts, it's more redundant but more accurate. Using 8 measurements instead of 2 makes the estimation more accurate. In each equation we must put the extintion coeff. of the different wavelenght. But the idea actually is to implement a statistical approach, in which... next slide

FIGURE 6.26. Simplified diagram of a typical ear oximeter. (Hewlett Packard product, reprinted after Mendelson, 1991, p. 268, courtesy of Marcel Dekker Inc., New York.)

Noninvasive oximetry

to increase the light flow with increasing temperature

Lamp = high-intensity and wide-spectral range tungsten light source
Filter: it determines 8 different wavelengths
Ear Warming at about 41°C, to augment blood flow and “arterialize” the blood
Signal processing: based on the following equation

$$SO_2 = \frac{a_0 + \sum_i a_i \cdot d(\lambda_i)}{b_0 + \sum_i b_i \cdot d(\lambda_i)}$$

constant

Linear combination of different absorbances/reflectances for the different w.l.

ai, bi, estimated previously by calibration, but done with linear REGRESSION!

(which is a general form of the equation seen before)

$\Rightarrow$ Linear regression to estimate a and b parameters.
Accuracy ≈2.5%

Pulse-oximetry

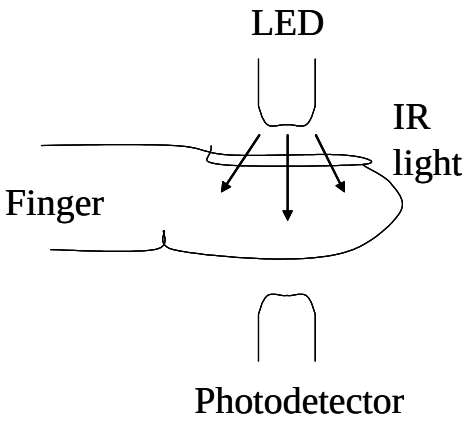
It is based on the measurement of the variation of transmitted light through the skin due to arterial pulse.
The signal varies due to the variation of the blood quantity in the tissues.
The optical signal is sampled at two different wavelength (e.g., 660 nm and 805 or 940 nm).
Signal processing: still based on the equation

L'ideal è letteralmente la stessa però abbiamo realizzato che possiamo valutare anche l'andamento della quantità del sangue

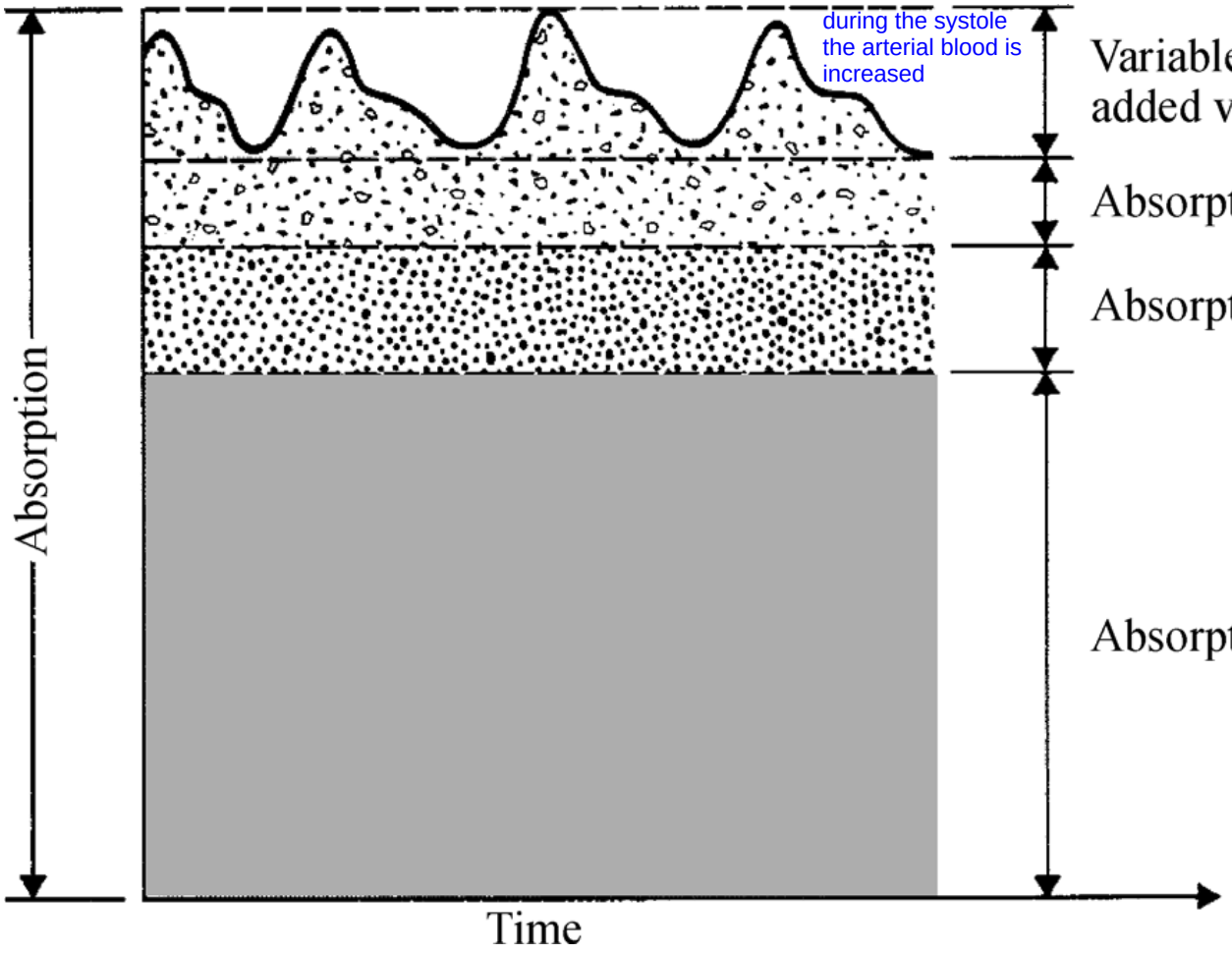
$$SO_2 = SpO_2 = \frac{a_0 + \sum_i a_i \cdot d(\lambda_i)}{b_0 + \sum_i b_i \cdot d(\lambda_i)}$$

+ linear regression to estimate a and b parameters.

Pulse Oximeters



Pulse-oximeter



The pulse oximeter analyzes the light absorption at two wavelengths of only the pulse-added volume of oxygenated arterial blood

Pulse-oximeter

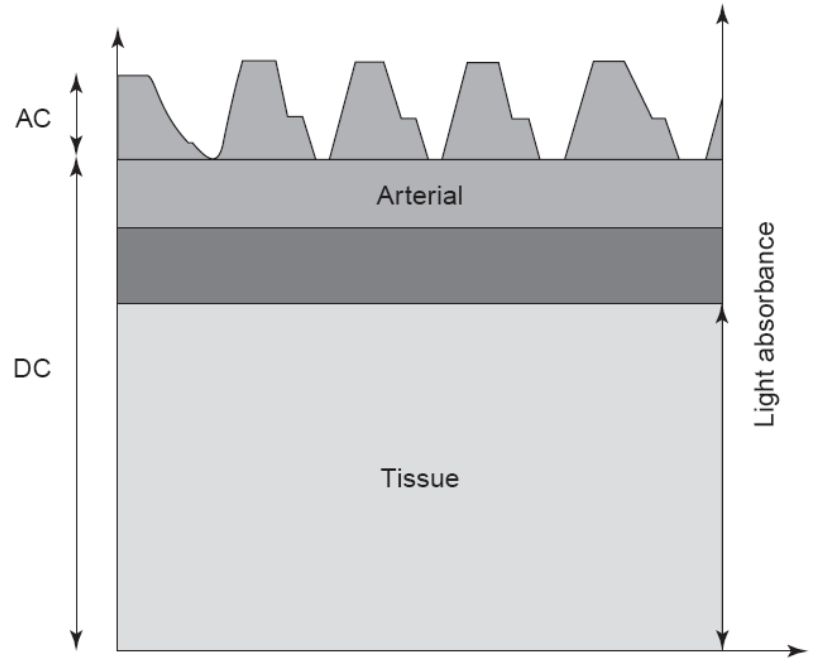


Figure 7. Light absorption by arterial blood, venous blood, bone, and tissue (7).

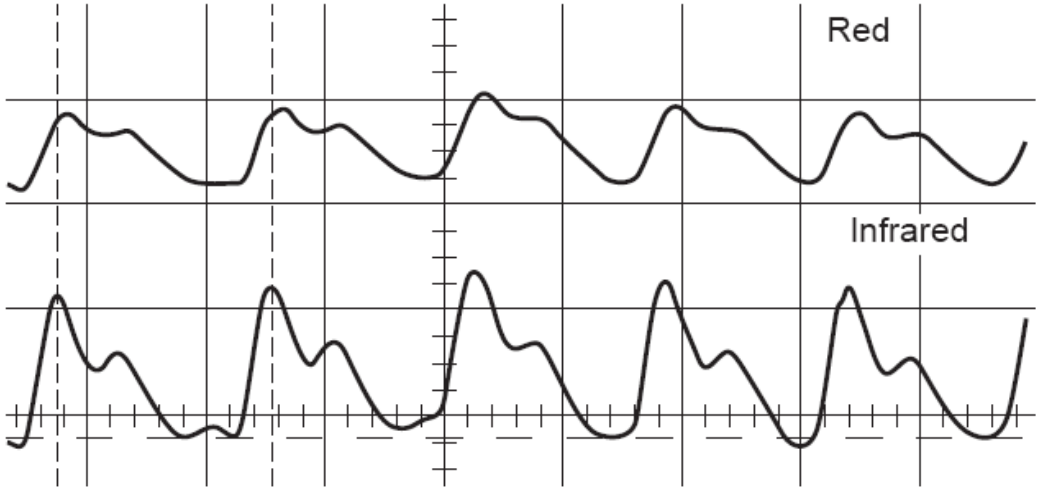


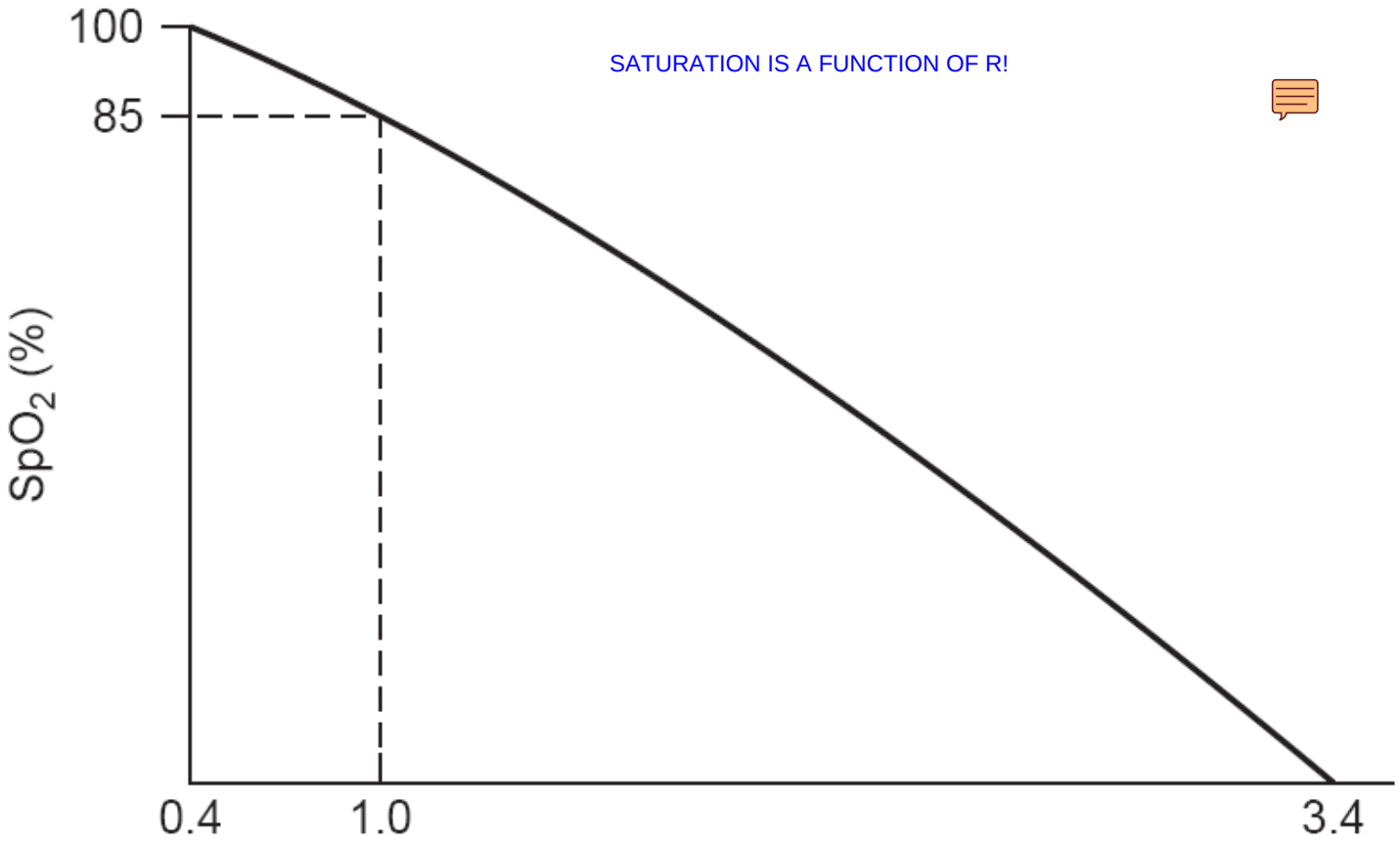
Figure 8. Transmitted red and infrared AC.

Letteralmente.. componente AC e DC dei due segnali :)

$$R = \frac{AC_R/DC_R}{AC_{IR}/DC_{IR}}$$

Pulse-oximeter: calibration

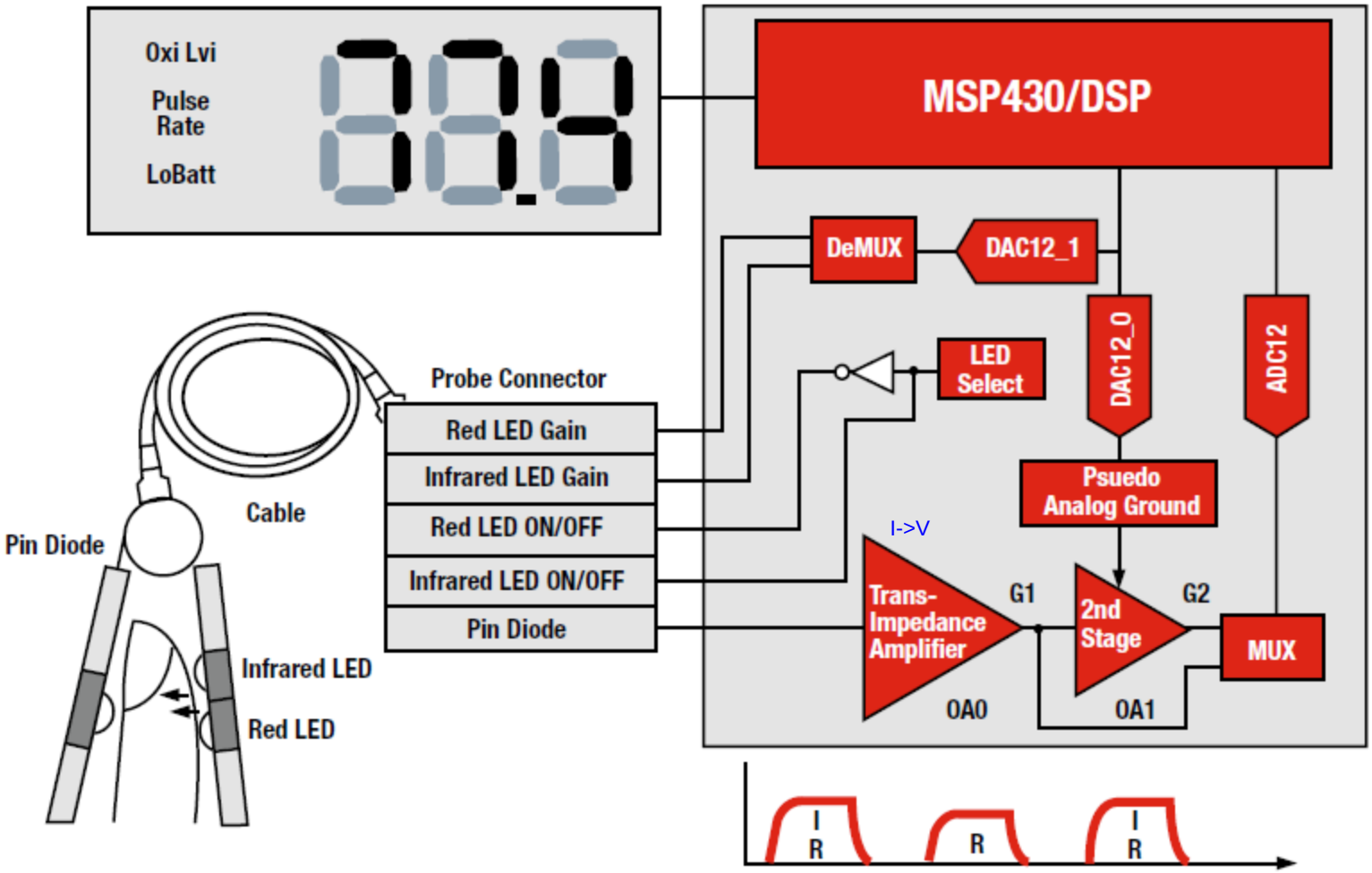
SATURATION IS A FUNCTION OF R!



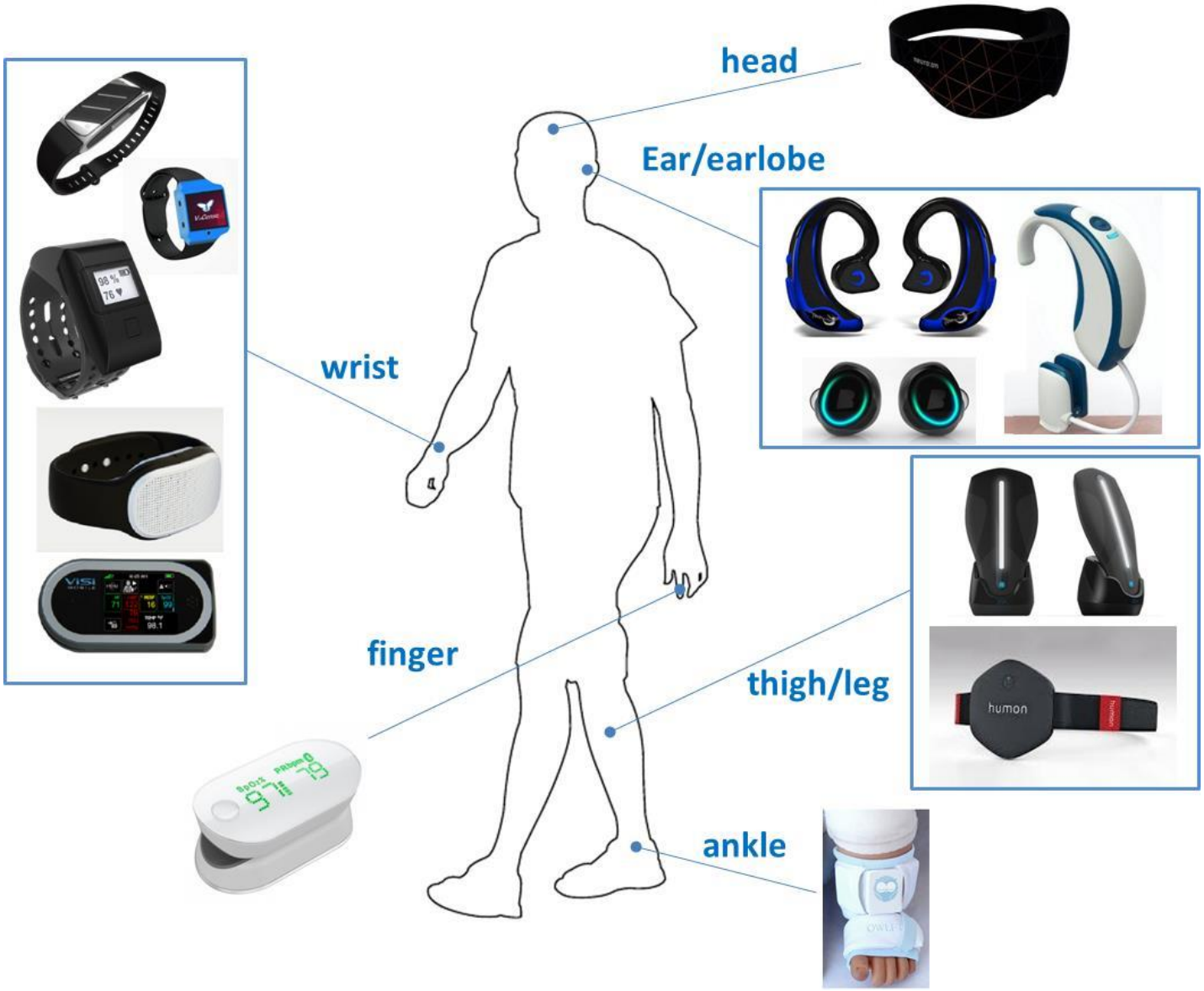
$$R = \frac{AC_{660}/DC_{660}}{AC_{940}/DC_{940}}$$

Figure 9. Typical pulse oximeter calibration curve (7).

Pulse Oximeter (example of electronics)



Wearable PPG systems



Wearable PPG systems

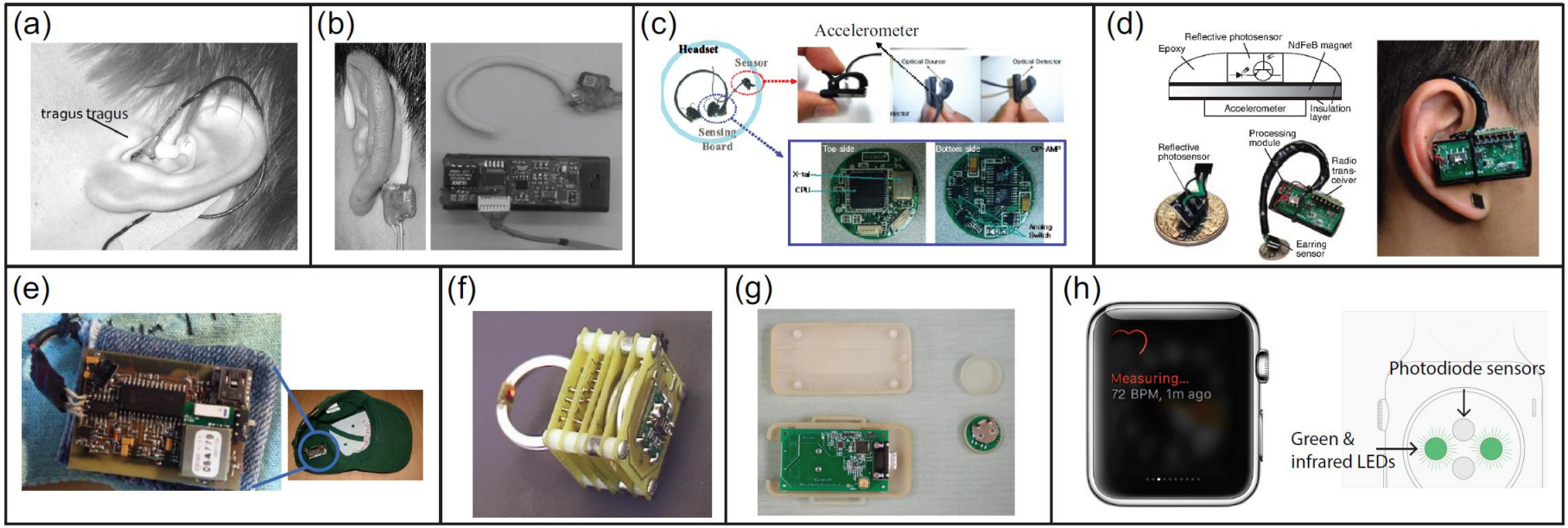
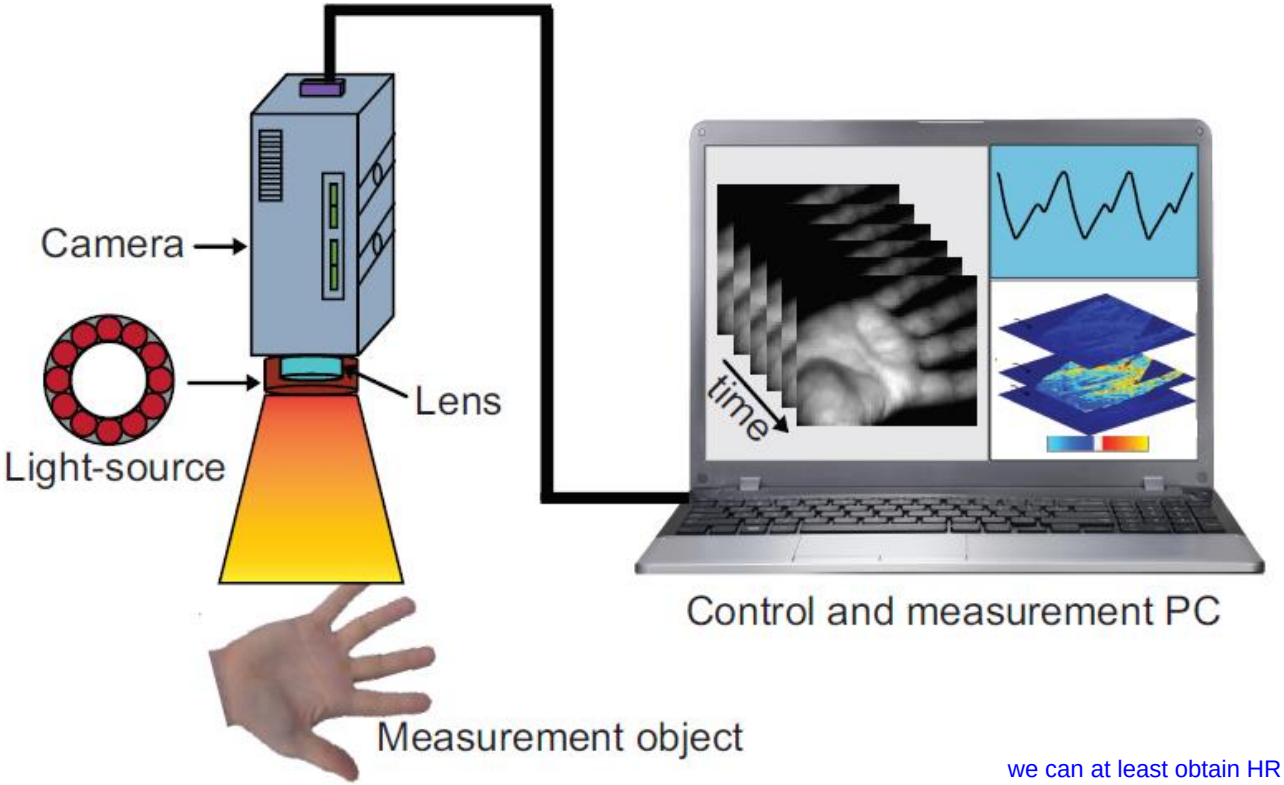


Fig. 3. Several representative types of wearable PPG sensors: (a) micro-optic reflective sensor with individually tailored otoplastic housing [24]; (b) ear-hook design of reflective sensor [25]; (c) an ear clip transmissive sensor with accelerometer [26]; (d) wireless magnetic earing sensor with accelerometer [27]; (e) a golf-hat with integrated wireless reflective sensor [28]; (f) a wireless transmissive ring sensor with accelerometer [29], [30]; (g) a wireless attachable reflective sensor with receiver module [31]; and (h) Apple Watch [32].

Yu SUN, Nitish Thakor. Photoplethysmography revisited: from contact to noncontact, from point to imaging. IEEE Transactions on Biomedical Engineering, in press

New trends: imaging PPG systems



we can at least obtain HR (not saturation tho') by just monitoring with a camera

Fig. 4. A schematic setup of an IPPG system which includes a light source and a camera. Physiological information (e.g., heart rate and perfusion) could be then extracted from the obtained images.

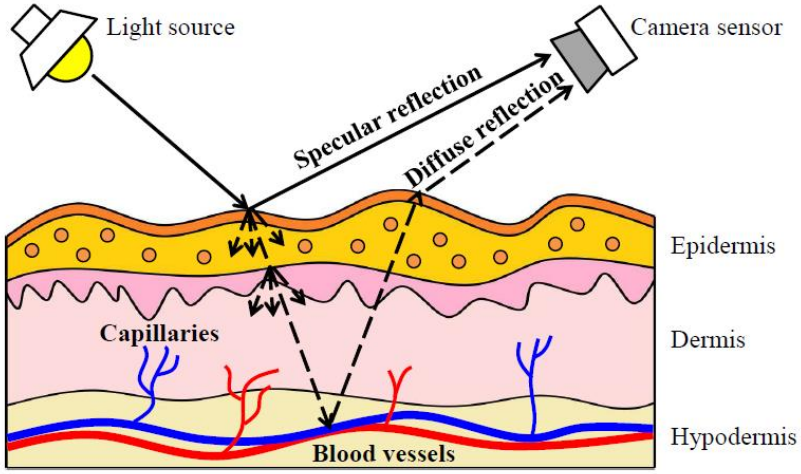
Yu SUN, Nitish Thakor. Photoplethysmography revisited: from contact to noncontact, from point to imaging. IEEE Transactions on Biomedical Engineering, in press

When light hits tissue two main fenomena happen:

- **Specular reflection**
  Light is reflected by the skin surface
  Same polarization of incident light
- **Diffusive reflection**
  Interaction with the tissue
  Change of polarization (random)

$$I(t)=I_0(t)*(S(t)+D(t))$$

Diffusive reflection is the only one that carries the PPG signal:
Reduce specular reflection by means of polarizing filters



System of polarizing filters on source of light and camera objective

- **P1 and P2 parallels:**
  Reduce the diffusive reflection
- **P1 and p2 orthogonals:**
  Reduce the specular reflection

$$I(t)=I_0(t)*(S(t)+D(t))$$

I can filterout the specular refletion