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REFLECTANCE AND TRANSMITTANCE TECHNIQUES FOR TRANSCUTANEOUS ARTERIAL OXYGEN SATURATION MEASUREMENT: A COMPARISON STUDY

I.A. CESTARI[1]

ABSTRACT -- A Transcutaneous Pulse Oximeter Prototype was built for operation in Reflectance or Transmittance mode. Analyses of the signals detected indicated that implications of optical characteristics of skin adjacent layers and background are stronger upon reflected intensities than transmitted intensities.

INTRODUCTION

The complexity of light interaction with a simultaneously absorbing and scattering medium such as the living tissue suggests the need of adopting simplyfing assumptions when quantifying the ligth transmitted or reflected through such a medium (Shuster,1905). This situation is well represented by the transcutaneous measurement of arterial oxygen saturation (OSa).

Commercialy available instruments designed for this purpose have their principle of operation based upon the two-wavelenght theory (Polanyi,1980) associated to a plethysmographic principle with a transmittance-based technique. This measurement must be performed at peripheral regions where light can be transmitted through and detected. However the accuracy of the measurement will be dependent on the degree of blood perfusion. A heating element is often utilized to increase blood flow through the regiom but it may cause some disconfort to the patient during chronic monitoring.

On the other hand, more centrally located areas which present a less variable degree of blood perfusion would be a more reliable site for measuring OSa thus requiring the application of optical reflectence rather than transmittance technique. The fact that there is no comercially available instrument based on a reflectance principle indicates the need of a more complete understanding of ligth interaction with living tissue. The present purpose is to compare both techniques within the scope of transcutaneous pulse oximetry.

[1] Bioengineering Division, Heart Institute
Av. Dr. Eneas de Carvalho Aguiar, 44 / SS
São Paulo, Brazil.

METHODS

Living tissue presents a large variability of its physiological charactheristics so that for the sake of simplicity it is valid to consider the skin, subcutaneous fat, and muscle tissue, each one associated with the blood filled capillaries as three separate and homogeneous layers (Longini, 1986). Thus considering multiple adjacent layers the net transmittance and reflectance will actually be a combined values which accounts for the respective contributions of the various layers (Kortum, 1969). The fat layer is generally considered highly reflective and the muscle layer has its optical behavior determined by its blood volume and respective hemoglobin content.

In the visible spectrum, skin pigmentation plays a large role in the reflectance and transmittance of skin by increasing the absorption of radiation in the most superficial layers whereas in the near infrared region, there is no significant difference in the spectral absorption curves between white and black skin (Hardy, 1956). Except for absorption due to water content and scattering, skin appears to be almost nonabsorbing in this region.

ARTERIAL OXYGEN SATURATION MEASUREMENT

Hemoglobin and oxyhemoglobin have different spectral molecular extinction curves and the absorption coefficient for HbO_2 is lowest in the red region (around 600 nm) while the absorption peak for Hb is higher (Horencker, 1943). The wavelength where both substances have equal coefficients is called isobestic (805 nm), and measurements made in this region of the spectrum are used as reference values.

Typical reflection or transmission signals will be amplitude modulated by arterial pulsation with a time variant component (AC) of the signal origenated by its blood content and a DC component due to the non blood tissue content. During a diastole most of the red light is absorved by venous blood and during the systole absorption is also due to the arterial blood. As blood oxygenation decreases, there is more absorption of red light and consequently the amplitude of the plethysmographic pulse corresponding to the red wavelength increases while a lower DC light intensity is detected. The AC and DC signals obtained by the measurement at the infrared wavelenght, however, remain constant and therefore can be used for normalization.

Yoshiya et al, (1980), demonstrated that neglecting the the scattering of the light by the erytrocytes, OSa can be

determined transcutaneously according to the relationship expressed by:

$$OSa = A - B \cdot [Ir / I ir] \qquad [1]$$

where A and B are linear regression coefficientes related the specific absorption coefficientes of Hb and Hbo_2, Ir and Iir are the changes in the absolute value of the reflected light intensities measured at the surface of the skin for the red and infrared wavelength, respectively. They represent the variation of the AC reflected light normalized to the DC component.

A Prototype Transcutaneous Oximeter was built (Cestari, 1985) with its operation based upon the assumption that the relationship expressed in Eq. 1 can be applied to describe the transmission and reflection of light from blood.

The signal detected can be influenced mainly by: skin and blood physiological properties, the luminous intensity incident upon the skin, the sensitivity of the photodetector, which is function of wavelength and optical coupling dictated by sensor geometry, and the noise inherent to the instrument's circuitry.

The main portion of the system, consists of a) an optical transducer which contains red and infrared LED's and a photodetector b) an analog processing circuitry consisting of the LED's driver, a pre-amplifier, a demultiplexer which separates this signal into a red and infrared channel, a low pass, a DC subtractor circuit and c) a Data Acquisition System, that samples and digitizes the signal.

RESULTS

IN VITRO FINDINGS

In order to investigate the factors which influence the reflectance and transmittance signals, in vitro studies were realized utilizing blood tissue model designed to allow these factors to be controlled and adjusted independently.

Living tissue was considered as two homogeneous layers, representing its blood and non blood components respectively. The model structure consists of two vertically mounted compartments built with rigid transparent materials and separated from each other by a flexible polyethylene membrane. Each compartment is provided with two taps to allow for blood or saline to be injected or withdrawn from it. The desired blood

layer thickness, simulating the percent volume of blood in the tissue, is obtained by varying the volume of saline and blood injected.

A light source (containing red and infrared LEDs) and a photodiode was mecanically coupled to the blood compartment surface to detect the portion of incident light reflected by the blood layer and a second photodiode was mounted on the opposit side (saline compartment surface) to detect the light transmitted through the blood layer. Background reflectance was also considered in this model by adapting a pelicule of reflective (aluminum foil) or absorbing (black rubber) material over the saline surface compartment.

The X-Y plot of figure 1 shows two sets of curves of reflectance versus transmittance of blood layer with varying thickness and background obtained for red and infrared wavelengths. The light intensities were measured in volts while continuously increasing the blood layer thickness from X2 = 0 mm to X1 = 2.75 mm.

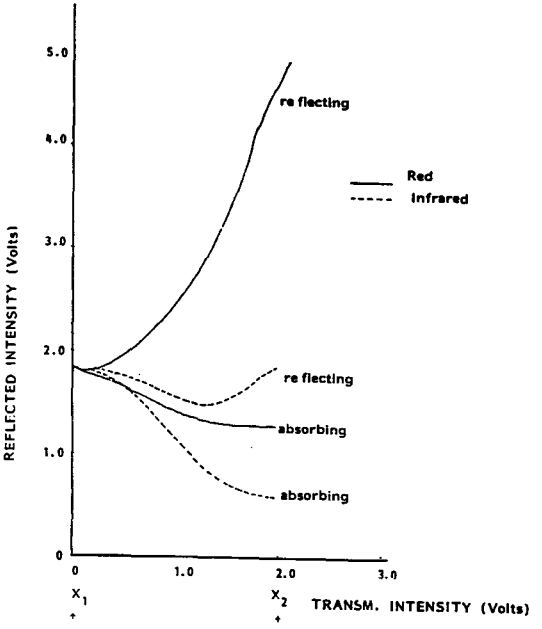

Figure 1 - X-Y Plot of transmitted versus reflected intensities for varying blood layer thickness and background optical characteristics.

It can be seen from the figure that for an ideally reflecting background and infinitesimal thickness both reflected and transmitted intensity are maximum. The blood sample used in these experiment was kept at a constant oxygen saturation of 80%. Indeed, if this is made a variable parameter, a family of curves will be obtained for the same background and the same thickness.

To investigate background influence on pulsatile signals a pulsatile blood pump (45 b.p.m. / 0.1 cc) was connected to the blood chamber. For a highly reflective background, the reflected and transmitted pulses obtained were in phase. For a highly absorbing background, the reflected light intensity arised only from the pulsing blood layer itself, therefore it followed the same trends of the pulse volume. The transmitted intensity maintened an inverse relationship to the blood volume in both cases. The data clearly demonstrated that, for the same pulse volume and the same OSa, different AC to DC ratios can be encountered in the reflected signals, depending on the background characteristics.

IN VIVO RESULTS

It is known that several regions present different vascular response to variations in ambient temperature. As already mentioned, increase in ambient temperature may cause peripheral regions to vasodilate thus increasing transmitted signal. To evaluate this effect upon reflected signals, two regions distinctly located in relation to the body core were tested for regional changes in cutaneous blood flow: the right side of the upper chest and the lateral upper arm. The signals detected showed a significant increase in the magnitude of their AC components (figure 2 below), which resulted from the light reflecting off a greater volume of blood in the capillares caused by cutaneous vasodilation (the DC component of the signal was maintained at a constant level by manual adjustment). These results indicate that the application of heat and consequently arterializing a specific location of the skin is a helpful procedure for improving the signal extracted from poorly perfused regions.

Besides varying the arterial blood volume of the finger it was attempted vary the finger's content of venous blood. A sphygmomanometer cutt was applied to upper arm of a healthy male subject, who had a blood pressure of 110/80 mm Hg with normal body temperature and constant OSa at the time of the measurement. The reflected intensities obtained are shown in figure 2 along with the stepwise increments produced in cuff pressure. For cuff pressure above 80 mm Hg the waveforms were damped and above 90 mm Hg the pulses of the red channel were inverted in relation to each other. When the cuff pressure was raised to 110 mm Hg, the pressure was vanished.

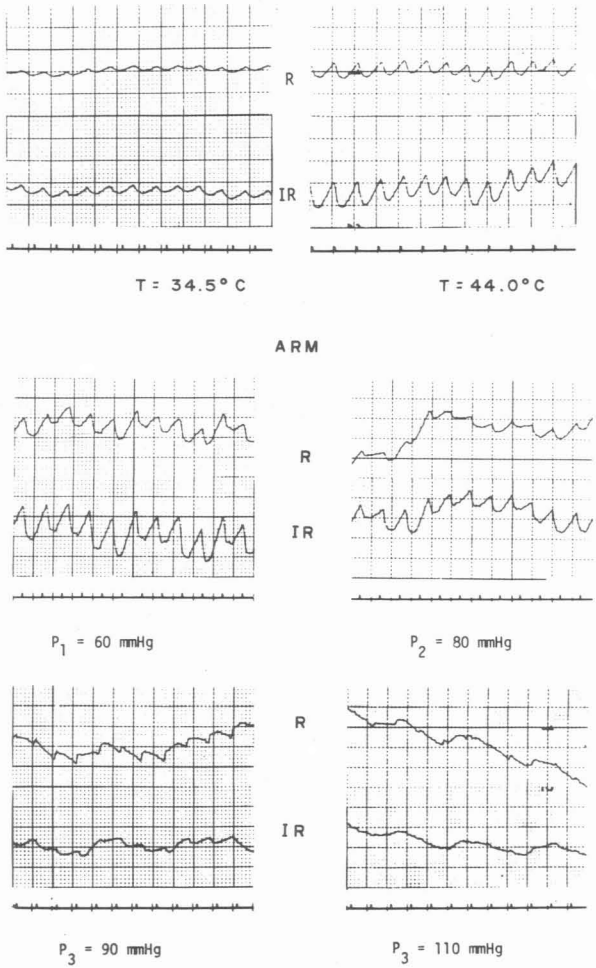

Figure 2. Effects of Temperature (a) and Pressure (b) variation upon the vascular state and respective changes upon reflected red (R) and infrared (IR) signals.

In fact, both the magnitude and sign of the ratio may change for reflected pulses while in a similar type of experiment the transmitted signals remained in phase (red and infrared) untill the cuff pressure was so elevated that the pulse could not be detected any more.

CONCLUSION

Obtaining reflectance data from centrally located regions certainly extends the range of apllications and reliability of transcutaneous oximetry. For skin and tissue under normal physiological conditions we primarily encounter a reflecting background where the reflectance and transmittance pulses are in phase. However, under extreme conditions which create an absorbing background inverted pulses may be detected.

The in vivo reflectance measurement lead to the finding that the reflected signal is strongly influenced by the optical properties of the background, therefore each signal would require a particular treatment since the total reflectance is actually a combination of reflected intensities originating from various tissue components such as: skin layer, muscle layer, fat layer, etc.

DISCUSSION OF THE RESULTS

Analysing the principle described by Eq.[1] for determining OSa in view of the results mentioned above is seen that it might not be adequate for accurately estimating the arterial oxygen saturation since it does not account for background contributions, i. e. the reflected intensity measured at the infrared wavelength does not compensate for all variations found in the optical properties of human living tissue.

However it can be applied for specific regions, whose optical properties are well studied and taking into account when designing the optical transducer.

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