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Application of a Fiber Optic Probe for Blood Oxygenation Measurement Using Near Infrared Spectroscopy

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Abstract

In this paper, the design and development of dual wavelength noninvasive fiber optic probe based oxyhemoglobin sensor has been presented. This instrument can be used for real time monitoring contents in the blood. It is well known that in blood, the oxygen is carried by the hemoglobin. It uses the dual wavelength spectroscopy which can be performed on blood to determine the oxyhemoglobin saturation. The two sources used are of wavelength 632.8 nm and 830 nm. Two probes containing a bundle of fibers are designed out of which two are source fiber and one is detector fiber. Two finger holders are also designed to prevent any variation in intensity due to finger movement. The backscattered intensity and transmitted intensity of red light and near infrared light are measured. With the help of the ratio of the backscattered intensities and transmitted intensities of red light and near infrared light, oxyhemoglobin saturation is determined.

Keywords: Blood oxygenation; Measurement; Oxygen saturation measurement; Near infrared spectroscopy

Introduction

Clinical need for cerebral oxygenation monitoring

In many areas of medicine and physiology, non-invasive study of living tissue oxygenation, in vivo is of great importance. It is believed that damage to the brain of an infant is caused by low arterial blood oxygenation and abnormal cerebral blood flow mostly. Hypoxic ischaemic i.e. damage to the central nervous system cells due to lack of oxygen is one of the major causes of cerebral atrophy (loss of brain tissues). Therefore, it is very much desirable to have a method of detecting hypoxic ischaemic in early stages as it is the commonest cause of permanent neurodevelopement disorder**.** In the past, Oximetry, Respiratory Chain Enzymes and Near Infrared Spectroscopy (NIRS) were some of the optical methods for determining blood and tissue oxygenation. In addition to the optical methods some other techniques such as Nuclear Magnetic Resonance Spectroscopy (NMRS) and Positron Emission Tomography (PET) can also be applied to non-invasive study of brain. NIRS monitoring offers the possibility of bed-side monitoring which NMRS and PET cannot meet [1].

Theory of Near Infrared Spectroscopy

The relatively good transparency of biological materials in the near infrared region of the spectrum permits sufficient photon transmission through organs for the monitoring of cellular events. The absorption of photons through biological materials occurs at specific wavelengths, determined by the molecular properties of materials in the light path. Above 1300 nm i.e. IR region water absorbs all photons over a path length of less than a few mm. below 700 nm i.e. in the visible part of spectrum intense absorption by hemoglobin and intense scattering prevent transmission over longer path lengths. However in the NIR region, from 700 nm to 1300 nm range, a significant amount of radiation is effectively transmitted through living tissues over longer distances [2].

In NIR range, the major absorptive tissues include hemoglobin, cytochrome aa3, and water and skin melanin. Whenever there is a change in blood supplement in regional cortex, hemoglobin changes significantly whereas cytochrome aa3 and skin melanin contents do not change much. This idea offers an opportunity to measure the cortex hemodynamic changes with NIR spectroscopy.

Optical Absorption of Hemoglobin

Hemoglobin is an iron containing protein with a molecular weight of 64450. It occurs in a no. of forms such as oxygenated hemoglobin (HbO_2), deoxygenated hemoglobin (Hb), carboxy-hemoglobin (HbCO), hemiglobin and sulfhemoglobin (SHb). The NIR optical effect of HbCO in vivo is negligible because of its low specific extinction coefficient. Hemiglobin and SHb are present in small concentration, therefore their effect is ignored [3].

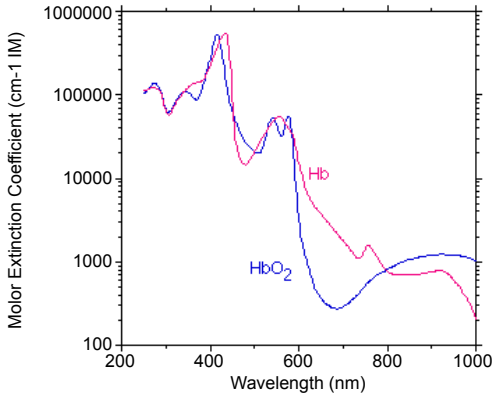

Figure 1: The absorption properties of haemoglobin.

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Thus, at NIR wavelengths, absorption is due to only two forms HbO_2 and Hb. Figure 1 shows the absorption properties of hemoglobin. Deoxygenated hemoglobin exhibits a weak absorption peak at 650 nm whereas oxygenated hemoglobin shows a peak at 830 nm. This allows the spectroscopic separation of the compounds. By measuring the tissue absorbency at these two wavelengths, we can determine the oxygen content in the blood [4].

Monitoring of Oxygen Saturation in the Finger

Non–invasive blood gas monitoring is essential to the patient with respiratory failure. It measures the oxygen saturation of arterial blood by analyzing the change in the optical density of the transmitted light with the inflow of arterial blood into the fingertip. Most of these instruments determine oxygen saturation (OS) by illuminating the blood with red and near infrared light and assuming a linear relation given as

$$OS=A - B (I_{ir}/I_{red})$$

where A and B are constants depending on physiological conditions and I_{ir} and I_{red} are back scattered intensities in the infrared (800-1000 nm) and red (630-670 nm) regions of the spectrum respectively.

The rationale behind the determination of OS from ratio of back scattered intensities measured at the two wavelengths rather than from the single wavelength is that the ratio metric technique reduces errors caused by variations in source intensity, blood flow, hematocrit and other factors. The sensitivity of the intensity ratio to OS is maximum as the difference in the absorption coefficient of Hb and HbO_2 is large at one source wavelength i.e. 600 nm and 660 nm and is very small or equal to zero between 805 nm to 1000 nm. At the isobestic wavelength 805 nm the absorptivities of the two forms of hemoglobin are equal [5]. Hematocrit and source-detector separation also affect the intensity ratio. The intensity ratio is highly sensitive to hematocrit variations at low OS. Around OS=80%, the ratio is nearly independent of hematocrit variations. Also, the relationship between OS and intensity ratio is linear when source and detector are closely spaced but sensitivity to OS increases with source-detector separation. The ratio becomes independent of source-detector separation around OS=80% [6-8].

Components of the Experiment

Reflection mode

A thin glass tube of 5 mm diameter fitted with bundles of fibers is used as a probe. The ends of the fibers are smoothened and polished in an optical workshop. Out of three fibers, two will go to two sources and one will go to the detector. A finger holder of glass with dimensions such that we can insert our finger inside it is made in the Glass blowing section [9]. It is needed as slight movement of finger may result in the variation of intensity. It has three outlets. From one of the outlets, probe is placed and from the other outlet the finger is put inside such that it just touches the probe (Figures 2 and 3).

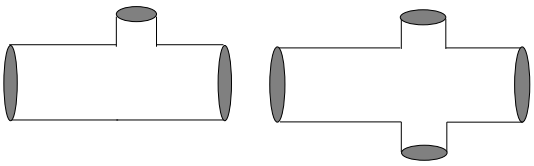

Figure 2: Finger probe (a) Reflection Mode (b) Transmission Mode.

Transmission mode

In the transmission mode out of three fibers of the probe two will go to two sources and a separate bunch of fibers is used for the detection process because the intensity of light detected in this process is low. In the finger holder also, we have an additional outlet for detector [10].

Experimental setup

The set up for the experiment carried out to determine oxy-hemoglobin saturation is shown below. Two laser diodes of wavelengths 632.8 nm and 850 nm are used. A cardboard was placed in front of both of them [11]. Initially red light was allowed to pass by removing the cardboard in front of it (Figure 4).

The finger of the subject was placed inside the finger holder. A sphygmomanometer was applied on the subject and the corresponding back scattered intensity of red light was noted down from the detector at different pressure applied from 0 mm to 120 mm in the steps of 10 mm of Hg. Similar procedure was carried out for the infrared light source. This process was repeated on three subjects in both reflection and transmission mode. We expected that the ratio (I_{ir}/I_{red}) should vary linearly with pressure but a second order empirical formula was obtained in both the transmission as well as reflection mode [12].

In transmission mode

$$Y=0.0004X^2 - 0.0064X + 0.0434,$$

and in reflection mode

$$Y=-0.0278X^2 + 0.0922X + 4.4983$$

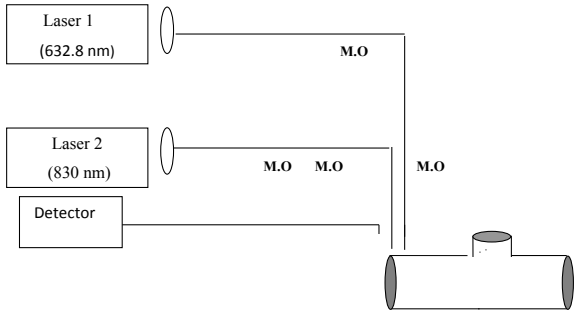

Figure 3: Experimental setup in Reflection mode.

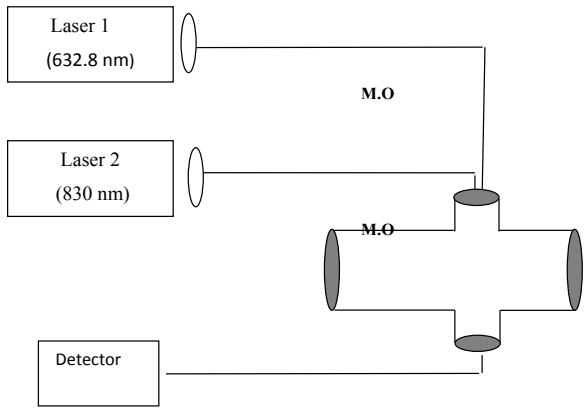

Figure 4: Experimental setup in Transmission mode.

Here Y=Ratio (I_{ir}/I_{red}) and X=OS=Experimental oxygen saturation.

The values of OS so obtained are compared with the standard values of OS obtained with the help of pulse oximeter.

Result

The Results are given in Tables 1, 2 and Figures 5-14.

Observations in Transmission Mode										
S.No.	Pressure (mm Hg)	Subject 1			Subject 2			Subject 3		
		I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter	I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter	I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter
1	0	19	0.332	97	19.5	0.326	99	19.7	0.322	98
2	20	18.5	0.332	97	19.2	0.326	98	19.0	0.322	98
3	30	18.3	0.332	96	19.1	0.326	97	18.7	0.322	97
4	40	18	0.332	96	18.9	0.326	97	18.1	0.322	97
5	50	17.6	0.331	96	18.5	0.325	97	18.0	0.322	97
6	60	17.3	0.330	95	18.3	0.325	96	16.8	0.320	96
7	70	17	0.330	95	18.0	0.324	96	15.0	0.319	96
8	80	15.3	0.330	94	16.2	0.323	95	13.2	0.319	95
9	90	14.8	0.328	94	14.7	0.322	94	12.2	0.319	94
10	100	11.9	0.328	93	12.5	0.321	93	11.1	0.319	93
11	110	9.2	0.328	92	10.8	0.320	92	9.9	0.318	92

Table 1: Observation table in Transmission Mode.

Observations in Reflection Mode										
S.No.	Pressure (mm Hg)	Subject 1			Subject 2			Subject 3		
		I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter	I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter	I_r (nW)	I_{ir} (μW)	OS by Pulse Oximeter
1	0	1.058	3.57	97	1.053	4.02	99	1.050	3.52	98
2	20	1.048	3.57	97	1.046	4.02	98	1.046	3.52	98
3	30	1.032	3.57	96	1.038	4.01	97	1.037	3.52	97
4	40	1.018	3.56	96	1.025	4.00	97	1.016	3.52	97
5	50	0.995	3.56	96	1.005	4.01	97	0.992	3.52	97
6	60	0.982	3.56	95	0.975	4.02	96	0.980	3.50	96
7	70	0.883	3.56	95	0.935	3.98	96	0.928	3.48	96
8	80	0.860	3.57	94	0.835	3.96	95	0.853	3.48	95
9	90	0.834	3.55	94	0.800	3.96	94	0.712	3.48	94
10	100	0.685	3.56	93	0.750	3.96	93	0.653	3.47	93
11	110	0.986	3.54	92	0.946	4.02	92	0.822	3.47	92

Table 2: Observation table in Reflection Mode.

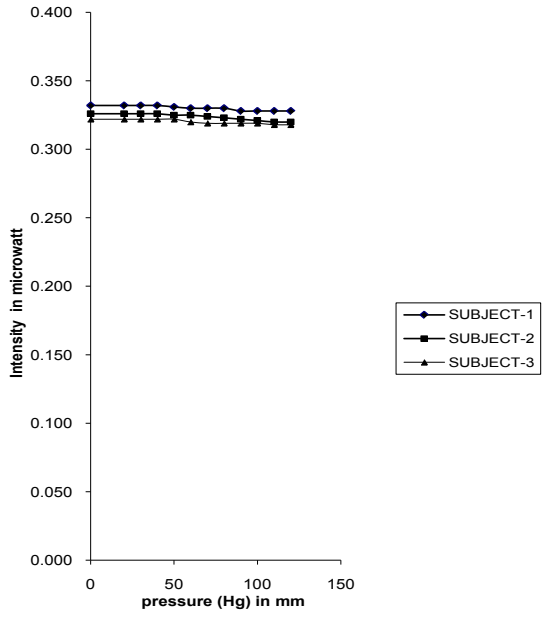

Figure 5: Variation of intensity of IR radiation with pressure [Transmission mode].

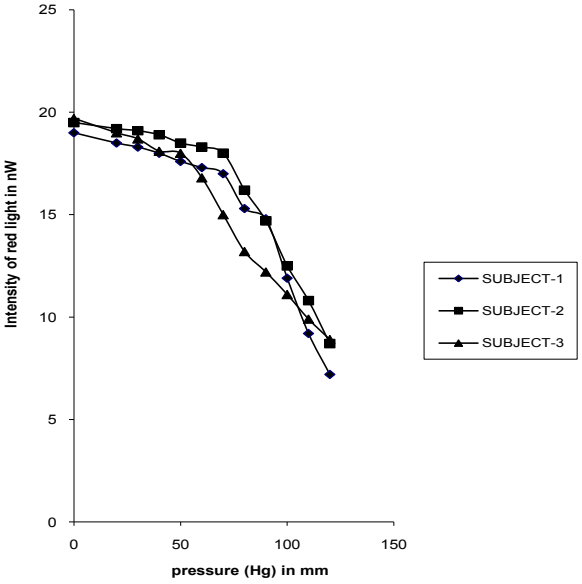

Figure 6: Variation of intensity of Red radiation with pressure [Transmission mode].

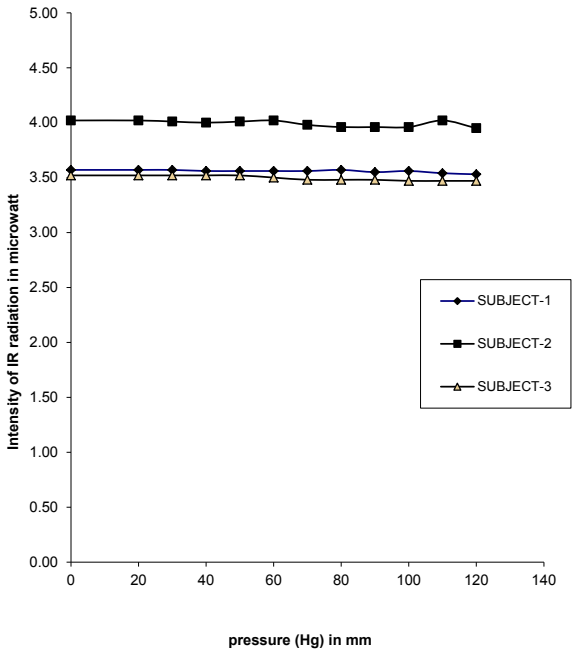

Figure 7: Variation of intensity of IR radiation with pressure [Reflection mode].

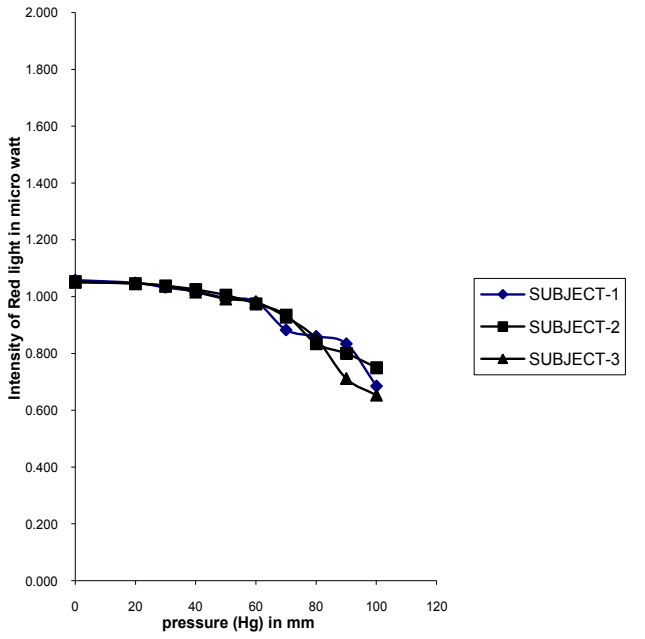

Figure 8: Variation of intensity of Red radiation with pressure [Reflection mode].

Discussion

In the experiment when pressure was applied through the sphygmomanometer, blood flow and hence oxygen supply in the arm was reduced. It led to increase in concentration of Hb and hence OS decreases. Hb has an absorption peak around 650 nm. As the pressure is increased, concentration of Hb increases which increases the absorption of red light [13]. So the intensity of red light decreases in

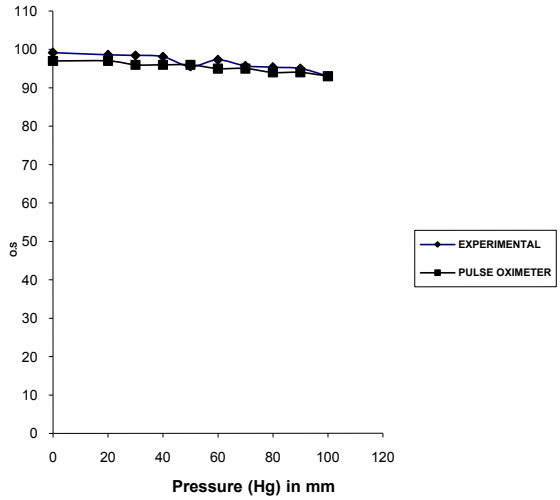

Figure 9: Comparison of Experimental O.S with the Pulse Oximeter Subject-1 [Reflection Mode].

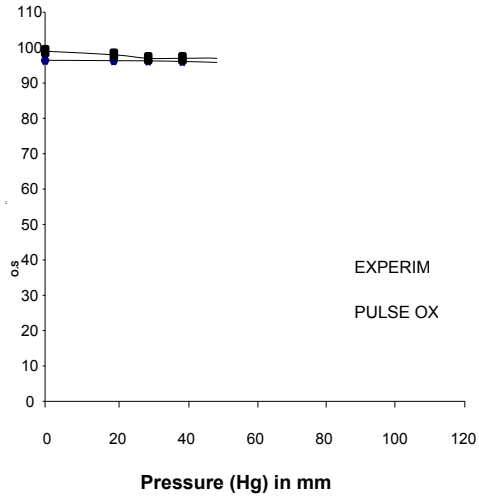

Figure 10: Comparison of Experimental O.S with the Pulse Oximeter Subject -2 [Reflection Mode].

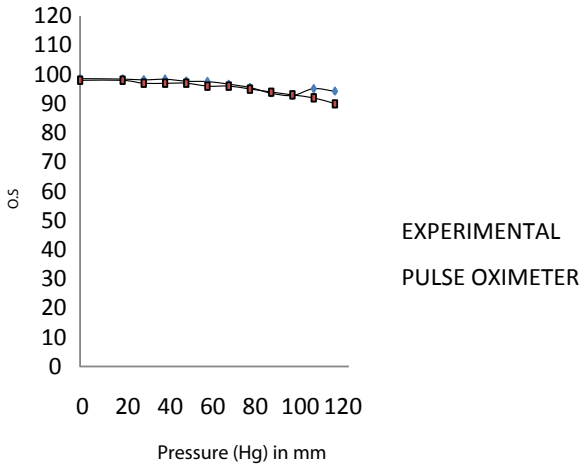

Figure 11: Comparison of Experimental O.S with the Pulse Oximeter Subject-3 [Refletion Mode].

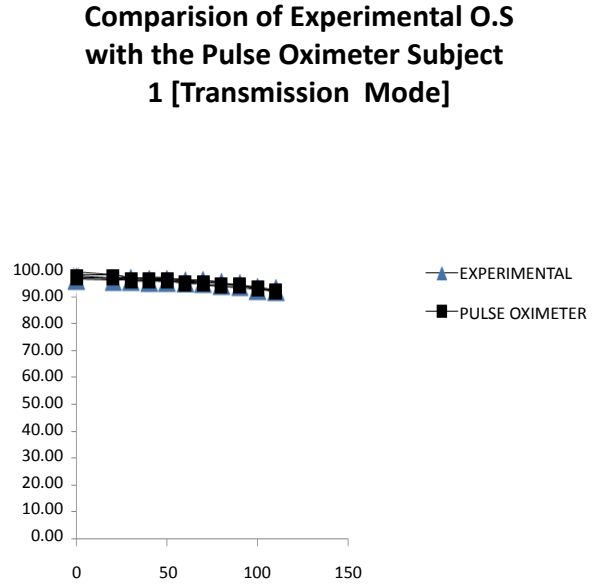

Figure 12: Comparison of Experimental O.S with the Pulse Oximeter Subject-1 [Transmission Mode].

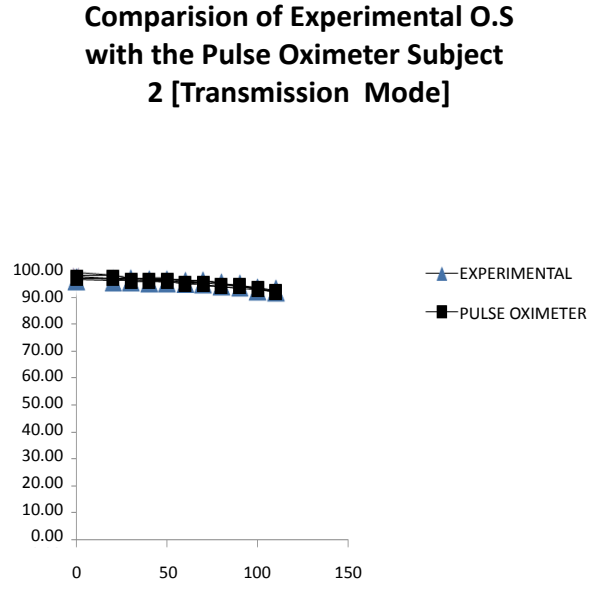

Figure 13: Comparison of Experimental O.S with the Pulse Oximeter Subject-2 [Transmission Mode].

both reflection and transmission mode. In case of NIR wavelength 830 nm, near to isobestic wavelength a small decrease in the intensity of light is observed with rise in pressure because at isobestic wavelength Hb and HbO_2 have same absorption peak. According to empirical relation, the graph between pressure variation and OS must be linear but actually we fit a second order polynomial with the data. The non linearity is only at high pressure and it occurs due to the presence of hematocrit. We observe a sharp decrease in OS at high pressure only. Oxygen saturation readings are hematocrit dependent. Largest errors in OS are observed in hemodiluted blood (i.e. Hct <30%) and poorly oxygenated blood (SO_2 <40%). The number, location and numerical aperture of the fibers affect the calibration constants A&B [14]. Hence

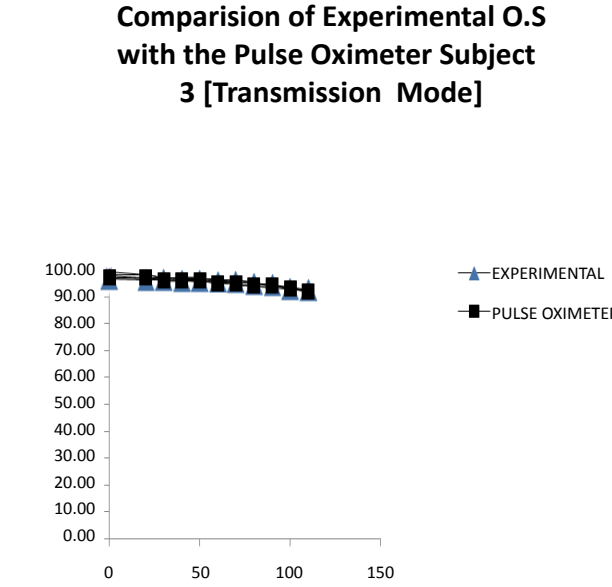

Figure 14: Comparison of Experimental O.S with the Pulse Oximeter Subject-3 [Transmission Mode].

the readings for the transmission or reflection geometry must be taken continuously. On increasing the distance between source and the detector the sensitivity will increase but simultaneously the linearity will decrease. Similar things happen with increase of hematocrit concentration.

Conclusions and Future Scope of the Work

Our experimental observations can be verified by placing our finger inside the finger holder and stop breathing for a while. It would result in the slow decrease in the output of red channel. After some time when the breath is resumed, an increase in the intensity of red light is observed. In the pressure experiment we have calculated the OS values by our experiment and compared it with values obtained from standard pulse oximeter. We get maximum 2% error. LED being small, rugged, and inexpensive and having narrow bandwidth are well suited for the experiment. They are available at discrete wavelengths in the visible as well as near infrared region. Typical values of source radii=0.25 mm, detector radius=0.5 mm and source-detector separation=0.8 mm give good linear relation between pressure and OS. The entire experiment must be done in dark room because ambient light can affect the results. Care must be taken while working at high pressure because backscattered intensity decreases gradually. Wait for some time before taking the readings. The finger support must be stable. Oxygenation measurement in the brain can also be done using this technique. But a photomultiplier would be needed for that because the intensity of back scattered light is too low to be measured.

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