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Non-invasive Measurement of Hemoglobin Concentration Using Magnetic Plethysmo Gram

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***Abstract*—A method for determining the concentration of hemoglobin in arterial blood, non invasively, is explored in this paper. A permanent magnet is placed just above the radial artery of a person whose hemoglobin concentration is to be ascertained. The flux produced by the permanent magnet (that links with the blood flow in the radial artery) is sensed to obtain a signal called magnetic plethysmogram (MPG). In this paper, an analytical model for a magnetic plethysmogram is derived. Using the proposed analytical model, a method of estimation of the concentration of hemoglobin in arterial blood is derived. The proposed method is then validated through a limited clinical study. The results of the clinical study establish the viability of measuring hemoglobin concentration, noninvasively, using magnetic plethysmogram.**

Keywords*— *Hemoglobin; blood volume pulse; magnetic plethysmogram; noninvasive measurement

I. Introduction

The concentration of hemoglobin cells in blood for healthy individuals varies in a range as given in Table I [1], [2]. If the heamoglobin concentration is less than that of the expected minimum, the deficiency is called anemia. Anemia can occur due to several reasons. For example, persons suffering from dengue may have lower than the expected hemoglobin concentration. Nearly 2 billion people worldwide suffer from anemia at any given time [2]. Since the main function of hemoglobin is to carry oxygen from the lungs to the tissues, anemia leads to hypoxia (lack of oxygen). Mild anemia is usually symptomless but in moderate cases, sufferers exhibit symptoms of tiredness and lethargy. Severe case of anemia can lead to dizziness, shortness of breath or even cardiac arrest. Conventional method of measurement of hemoglobin concentration in blood involves the extraction (drawing of blood by puncturing a vein) of a few millilitres of venous blood and using the hemiglobincyanide method [3]. Though the sodium lauryl sulfate (SLS) method [4] of ascertaining heamoglobin concentration in blood is less accurate than the hemiglobincyanide method, it is preferred since the hemiglobincyanide method involves the handling of toxic cyanides [5], [6].

We now present a novel non-invasive method of determination of hemoglobin concentration in arterial blood. The proposed method uses a simple probe to obtain a magnetic-plethysmogram (MPG) of the radial artery. Using the MPG, the hemoglobin concentration in radial artery (arterial blood) is determined. Since the method does not involve puncturing a vein or handling blood, it is best suited for home care applications.

TABLE I Normal Hemoglobin Levels in humans [1], [2]

Category	Age	Heamoglobin g/l
Children	6 months to 5 years	> 110
	5 to 11 years	> 115
	11 to 15 years	> 120
Women (not pregnant)	> 15 years	> 120
Women (pregnant)		> 110
Men	> 15 years	> 130

II. The Method of Magnetic PlethysmoGraphy

Plethysmogram is a signal that provides information on the blood volume changes [7]. Today, the Photo Plethysmogram (PPG) is a well known and well established technique [8]. A photo plethysmogram (PPG) is obtained by illuminating a section of the body with light at a particular wavelength and detecting either the transmitted light through the body or reflected light emanating from the body [9]. From the detected signal, the attenuation due to the blood volume changes are delineated and utilized for ascertaining:

(i) the heart rate [10],
(ii) the heart rate variability [11]
(iii) oxygen saturation in arterial blood [12] - [14],
(iii) venous refilling time [15] and
(iv) hemoglobin concentration in arterial blood [16].

Similar to the PPG, a magnetic plethysmogram (MPG) is obtained by exposing a section of the body with magnetic flux and delineating the component of flux that interacts with blood volume changes [17], [18]. To obtain an MPG, a permanent or electromagnet and a magnetic flux sensor are placed in close proximity to an artery. Fig. 1 shows the MPG sensor (made of a permanent magnet and a hall effect flux sensor) in close

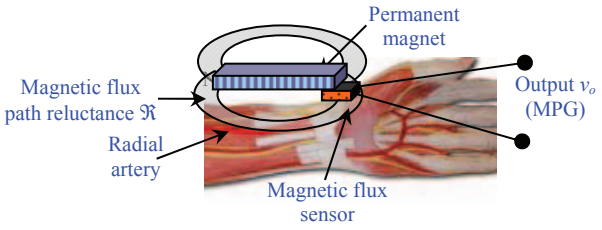

Fig. 1. Sensor system for obtaining an MPG

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proximity to the radial artery. Part of the magnetic flux produced by the permanent magnet interacts with the blood flow in the radial artery and hence the flux gets modulated by the blood volume changes. The magnetic flux sensor is positioned such that it senses the part of the flux ϕ that flows through the radial artery as can be seen in Fig. 1. The flux ϕ sensed by the flux sensor is determined by the magneto-motive-force generated by the permanent magnet and the magnetic reluctance $\Re$ of the flux path that includes the artery and can be written as:

$$\phi = \frac{M_m}{\Re}. \tag{1}$$

M_m in (1) is the magneto-motive-force (mmf) produced by the magnet and $\Re$ is the magnetic reluctance of the magnetic flux path, where:

$$\Re = \Re_m + \Re_a + \Re_s + \Re_t + \Re_b(t) \tag{2}$$

Here $\Re_m$ is the reluctance of the magnet, $\Re_a$ is the reluctance of the flux path in air, $\Re_s$ is the reluctance offered by the magnetic flux sensor, $\Re_t$ is the reluctance offered by parts of the body such as epidermis, dermis and bloodless tissue and $\Re_b(t)$ is the reluctance offered by blood. If we assume that the area of the flux path in Fig. 1 is A_ϕ then:

$$\Re_m = \left(\frac{1}{\mu_o A_\phi}\right)\left(\frac{l_m}{\mu_m}\right),\ \Re_a = \left(\frac{l_a}{\mu_o A_\phi}\right),\ \Re_s = \left(\frac{1}{\mu_o A_\phi}\right)\left(\frac{l_s}{\mu_s}\right),$$

$$\Re_t = \left(\frac{1}{\mu_o A_\phi}\right)\left(\frac{l_t}{\mu_t}\right) \text{ and } \Re_b = \left(\frac{1}{\mu_o A_\phi}\right)\left(\frac{l_b(t)}{\mu_b}\right) \tag{3}$$

Here μ_o is the magnetic permeability of free space, μ_m is the relative permeability of the material with which the permanent magnet is made of, l_m is the length of the magnet, l_a is the path length of the magnetic flux in air, μ_s is the relative permeability of the flux sensor, l_s is the thickness of the sensor, μ_t is the relative permeability of tissue, l_t is the length of the path of the flux in tissue and μ_b is the relative permeability of blood and $l_b(t)$ is the length in the path of the flux occupied by blood.

It is to be noted here that the path lengths l_a, l_s and l_t do not vary with respect to time. While lengths l_a and l_s remain constant, l_t will change with time as tissue cells will die and get replaced by new cells. However, the time frame in which this change occurs is very large compared to the time window in which the measurement is made and the MPG is obtained. Hence for all practical purposes, l_t can be considered as a constant (with no significant change) within the window of time we obtain the MPG. Thus during the measurement window, only the path through the blood vessels vary as the blood vessels expand and contract due to variations in the volume of blood flow. Since the path length through blood vessels $l_b(t)$ is time varying, the reluctance $\Re_b(t)$ offered by the variation in blood volume changes varies in time, in the time window of measurement of MPG. Since the path lengths (l_a and l_s) are constants the reluctance $\Re_a$ and $\Re_s$ of these paths do not change with time. $\Re_t$ may change very slowly taking hours or even days, but within the time window of MPG measurement the change will be negligible and hence can be assumed to be a constant.

It is now well established that water is diamagnetic and hemoglobin is paramagnetic, especially at the level of magnetic flux encountered in an MPG system [19]. Hence the influence of plasma in blood in determining the flux will be negligible as plasma is nearly 99 % water. On the other hand haemoglobin which is paramagnetic with a relative permeability of 7.4 will alter the flux produced by the permanent magnet. Thus the magnetic parameters of air, tissue (skin and bloodless tissue) and haemoglobin in blood alone will determine the flux that is being detected by the magnetic flux sensor. With these conditions, equation (1) can be rewritten as:

$$\phi = \frac{M_m}{\Re_m + \Re_a + \Re_s + \Re_t + \Re_b(t)} \tag{4}$$

Equation (4) can be rewritten as:

$$\phi = \frac{M_m}{\Re_R\left(1 + \frac{\Re_b(t)}{\Re_R}\right)} \approx \frac{M_m}{\Re_R}\left(1 - \frac{\Re_b(t)}{\Re_R}\right) \tag{5}$$

Using (3), (5) can be rewritten as:

$$\phi \approx \frac{M_m}{\Re_R}\left(1 - \frac{\mu_R}{\mu_b}\frac{l_b(t)}{l_R}\right) \tag{6}$$

Here $\Re_R$ is the reluctance of the rest of the path of the flux other than blood and μ_R is the effective relative permeability of the rest of the flux path and l_R is the effective path length of the flux through all other parts, except the path through blood.

Of course (6) is valid if and only if

$$\frac{\mu_R}{\mu_b}\frac{l_b(t)}{l_R} << 1. \tag{7}$$

Here $\mu_b \approx 7.4\mu_R$ and the path length through air and tissue l_R will be in tens of millimeters and the path of the flux through blood $l_b(t)$ will be in millimeters. Since $\mu_R < \mu_b$ and $l_b(t) < l_R$, $\frac{\mu_R}{\mu_b}\frac{l_b(t)}{l_R}$ will be << 1. This flux is sensed by the

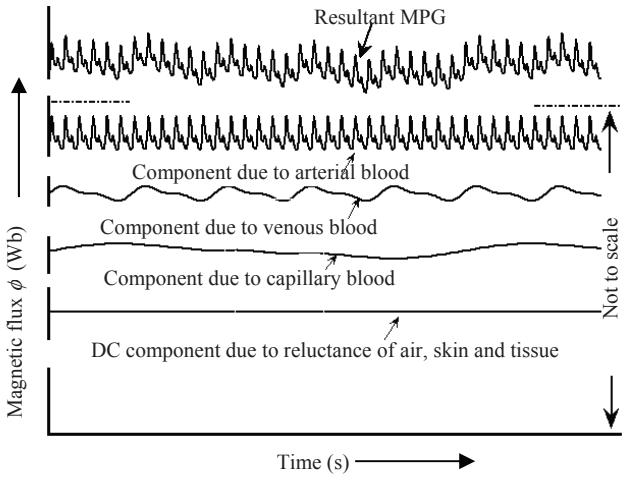

Fig. 2 Components of magnetic – plethysmo gram (MPG)

flux sensor and hence the output v_o of the flux sensor can be obtained as:

$$v_o = K_s \frac{\phi}{A_s} = K_s \frac{M_m}{A_s \Re_R} \left(1 - \frac{\mu_R}{\mu_b} \frac{l_b(t)}{l_R}\right), \qquad (8)$$

where K_s is the sensitivity of the flux sensor (in volts per tesla) and A_s is the area of the sensor in square meters. It is seen from (8) that the output of the flux sensor will consist a dc part $\left(K_s \frac{M_m}{A_s \Re_R}\right)$ and an ac part $K_s \frac{M_m}{A_s \Re_R} \left(\frac{\mu_R}{\mu_b} \frac{l_b(t)}{l_R}\right)$ made of three distinct time varying components as indicated in Fig. 2. It should be noted that in order to bring in clarity, each component in Fig. 2 is drawn with differing magnitude scales. While the dc part of the flux will be due to the reluctance of air, tissue, magnet and the sensor, the time varying part of the flux will be due to the flux path through:

(i) The blood flow in capillaries,

(ii) The blood flow in veins and

(ii) The blood flow in artery.

Such an output (dc + ac parts of the output of the flux sensor) is popularly called the magnetic-plethysmogram (MPG). It is easily seen that while the blood flow in capillaries will appear as a very slow varying ac in an MPG, the blood flow in veins will provide a slow varying ac signal in the MPG and the signal that emanates from the arterial blood flow will appear as pulsating in the MPG as indicated in Fig. 2.

Using (8), the pulsating part v_b of the MPG can be derived as:

$$v_b = v_o\big|_{\text{pulse}} = K_s \frac{M_m \mu_R}{A_s \Re_R \mu_b l_R} l_b(t) = K_p \, l_b(t), \qquad (9)$$

where $K_p = \frac{M_m \mu_R}{A_s \Re_R \mu_b l_R}$ is the MPG probe constant. Here $l_b(t)$ is the length of arterial blood-flux interaction. Since $l_b(t)$ varies as the volume of blood in the artery changes, the pulsating output v_b of the sensor as given in (9) indicates the changes in the blood volume. Blood contains ≈ 54 % of plasma and 45 % of red blood cells (erythrocytes) mostly made of hemoglobin. As has already been brought out earlier, plasma is made of water and hence has negligible contribution in determining the flux. Thus the pulsating output voltage in (9) is mainly due to hemoglobin content in arterial blood. Thus it is possible to compute the amount of hemoglobin in arterial blood using an MPG as illustrated next.

III. MPG System Design

The MPG system consist of:

(i) An MPG probe to sense the flux that links with the blood in the radial artery and

(ii) A data acquisition system to acquire the output of the flux sensor of the MPG probe.

The data obtained is processed to obtain the concentration of hemoglobin.

A. The MPG probe

The MPG probe was designed using a small cylindrical permanent magnet of 6 mm diameter and 2 mm thickness (Model D032A1 from Amazing magnets) and a hall effect sensor (Model SS49E SEC from Electronics Inc. of dimensions 4 mm width and 3 mm height with a thickness of 1.58 mm). The sensor was soldered to a small printed circuit board (PCB) and the permanent magnet was attached to the sensor such that the magnetic axis of the permanent magnet and the axis of sensing of the hall affect sensor are aligned. SS49E hall-effect type magnetic sensor has a linear input output characteristics, has a sensitivity of 2.2 V/T, has a flux sensing in the range: - 0.1 5T to + 0.15 T and an operating temperature in the range: – 40 °C to +85 °C. The excitation to the MPG probe was set as 5 V. The probe was calibrated using a standard flux meter manufactured by Siemens, Germany.

B. The data acquisition system

The data acquisition and processing are implemented with a personal computer (PC) fitted with National Instrument's (NI) 16-bit data acquisition (DAQ) hardware. The overall block

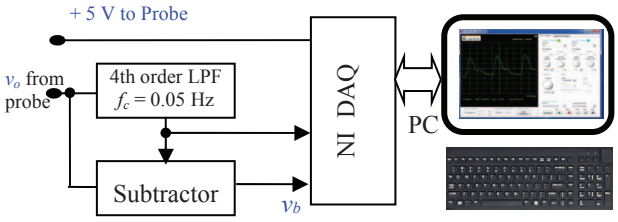

Fig. 3 The Data Acquisition System to obtain and process an MPG

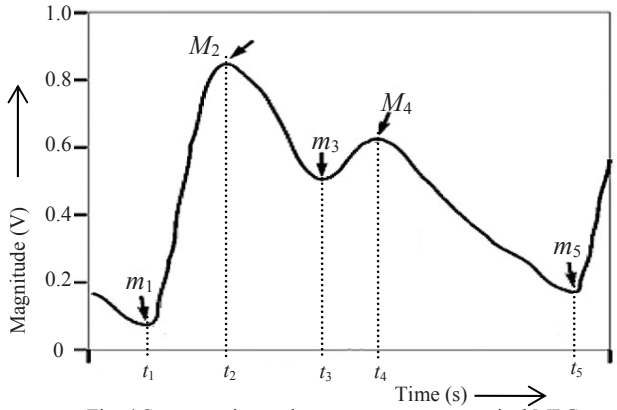

Fig. 4 Segmentation and measurements on a typical MPG (with a dichrotic notch)

diagram of the data acquisition system is shown in Fig. 3. The dc part of the output of the flux sensor was first filtered using a fourth order low pass filter (LPF) having a cut-off frequency of 0.05 Hz and pass band gain of 0 dB. The dc output thus obtained is then subtracted from the output of the flux sensor to obtain the pulsatile part v_b of the flux sensor. The output v_b of the subtractor is then acquired using the DAQ.

C. Acquisition of the MPG data

The acquisition, processing and display are accomplished through a virtual instrumentation (VI) developed under the NI LabVIEW environment. The output v_b was sampled at the rate of 10.0 k sa/s. On the start command, data on v_b is acquired for a period of one minute and stored in a file. At the end of acquisition, the processing begins. The processing steps are illustrated next.

D. Processing of the MPG data

The data on v_b is read from the file and the offset and trend are eliminated using the least square method. Then the first *minima*, say m_1 is determined and there from the data is segmented to delineate individual cycles. A typical cycle is portrayed in Fig. 4. The minima and maxima and their points of occurrences are identified in each cycle. Further processing starts once all the minima and maxima portrayed in Fig. 4 are identified. Starting from te first minim m_1, the succeeding maxima and minima are determined as indicated in Fig. 4.

Once the minima and maxima points are ascertained the algorithm developed starts from m_1 and then identifies the very next maxima (M_2) and the next lowest minima (m_5) points and their respective times of occurrence (t_2 and t_5) points. From these values, the magnitude P_1 and time period T_1 of the MPG cycle shown in Fig. 4 are computed as:

$$P_1 = M_2 - m_1 \quad \text{and} \quad T_1 = t_5 - t_1 \tag{9}$$

From the calculated value of T_1, the heart rate H_1 (in beats per minute) is computed as $H_1 = 60/T_1$.

This process is continued till all the MPG cycles, say n, in the one minute data are discovered. Then the corresponding n

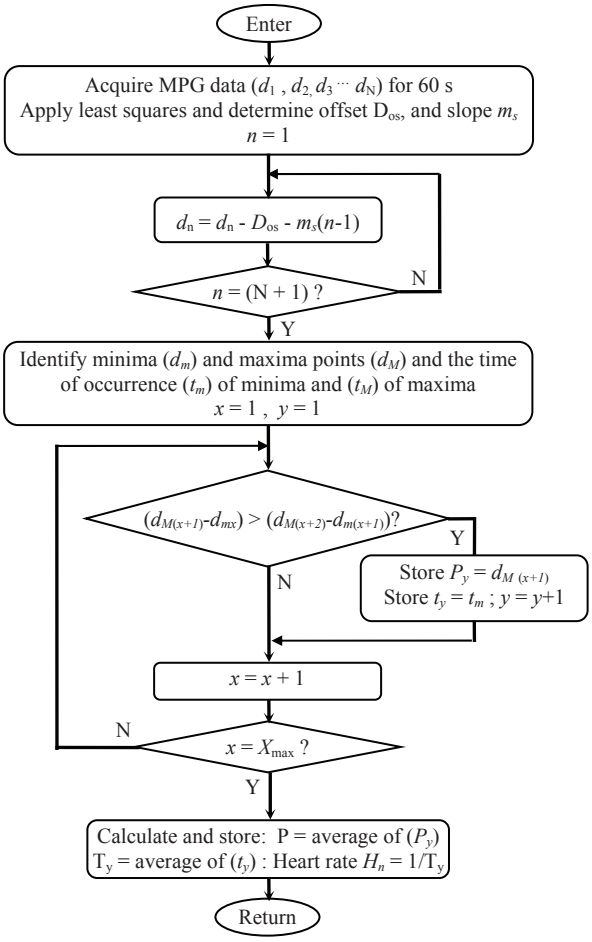

Fig. 5 Flow chart for determining the avearge magnitude of MPG and avearge period of MPG

values of the magnitudes (P_1, P_2, P_3 … P_n) and heart rates (H_1, H_2, H_3 … H_n) are stored for further processing. Using the set of heart rates (H_1, H_2, H_3 … H_n), the average heart rate and heart rate variability are computed and displayed [20]. Fig. 5 illustrates the procedure outlined above as a flow chart, which is self explanatory.

In order to determine the constant of proportionality between the magnitude of the MPG and the hemoglobin concentration, a limited clinical trial was conducted as detailed next.

IV. Clinical Trial and Experimental Resuls

Using the developed MPG acquisition system, a limited clinical study was conducted. The protocol followed was:

(i) The volunteer was made to relax on an arm chair for a small period of time (few minutes till the volunteer is comfortable).

(ii) Blood sample from the volunteer is extracted and hemoglobin content for the volunteer is obtained using the sodium lauryl sulfate (SLS) method [4].

TABLE II EXPERIMENTAL RESULTS OF LIMITED CLINICAL STUDY

Sl. Number	Gender	Age	Pulse Rate (beats per min)	Magnitude of MPG (V)	Hb concentration g/dL		Deviation (%)
					SLS	From MPG	
1.	F	43	82	0.62	13.0	13.3	2.31
2.	F	12	90	0.7	14.1	14.7	4.26
3.	F	33	81	0.6	12.8	13.0	1.56
4.	F	40	78	0.54	11.7	12.1	3.42
5.	M	53	80	0.72	14.7	14.8	0.68
6.	M	13	86	0.52	11.8	11.0	-6.78
7.	M	27	89	0.76	16.7	16.2	-2.99
8.	F	32	82	0.6	12.8	13.0	1.56
9.	M	38	75	0.74	16.0	15.3	-4.38
10.	M	26	82	0.66	14.2	14.1	-0.70

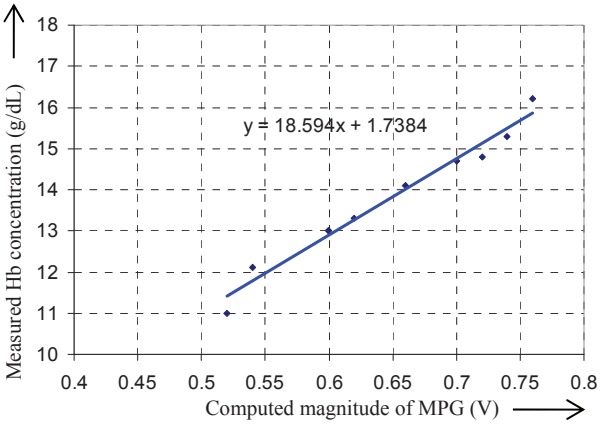

Fig. 6 Plot of measured Hb concentration against average peak to peak values of the MPG

(iii) To find the optimal position for placing the MPG sensor, the pulse of the volunteer is sensed using the index and middle fingers [22]. The sensor is placed on the wrist in that position where the pulse is sensed. Then the sensor is moved around that position so as to obtain a maximum value at the ouput of the MPG sensor. Once the optimal position of the MPG is found, data on MPG is acquired for one minute.

The protocol was approved by the institute's ethics committee. The acquired data is then processed. First, offset if any, present in the data set is removed from each recording of the MPG and the resulting MPG is de-trended to remove the baseline wander as illustrated in Fig. 5. Each of the processed MPG record is segmented to obtain individual MPG cycles as given in Fig. 4. The maxima and minima are then determined using the algorithm portrayed in Fig. 5. From the maxima and minima the peak to peak values $P_1, P_2, P_3 \ldots P_n$ and the periods $T_1, T_2, T_3 \ldots T_n$ of the segmented MPG cycles are determined. From the periods $T_1, T_2, T_3 \ldots T_n$ the heart rates $H_1, H_2, H_3 \ldots H_n$ are determined. From these heart rates, heart rate variability (HRV) is also obtained for each volunteer. Then the average value of the magnitudes the MPG (average of $P_1, P_2, P_3 \ldots P_n$ for each volunteer) is computed. The computed values are tabulated in Table II along with the hemoglobin concentration measured using the sodium lauryl sulfate (SLS) method. Table III shows the statistical analysis performed between magnitude (peak to peak) values of the MPG and the hemoglobin concentration for the ten volunteers listed in Table II. From Table III, it is seen that the p-value for a one-tailed test is 2.39 E-10, and p-value for a two-tailed test is 4.7 E-10, once again showing the statistical significance of using the MPG for determining hemoglobin concentration in arterial blood.

A plot of the hemoglobin concentration versus the average magnitude (peak to peak) values of the MPG for the ten volunteers listed in Table II is shown in Fig. 6. Equation (9) indicates that the magnitude of the MPG and the hemoglobin concentration must be linearly related. As expected in (9) the data plotted in Fig. 6 clearly shows that a straight line fit is possible through linear regression analysis. Such a straight line fit is obtained and plotted in Fig. 6. The deviation of the individual data from the linear fit and the measured hemoglobin concentration (measured using the SLS method) is calculated. The deviations from the actual measured hemoglobin concentration and the value ascertained from the MPG for each volunteer is also given in Table II. These results indicate that the MPG can be employed to measure hemoglobin concentration, non invasively.

The MPG probe is being further modified so that a measure of the flux that links with the radial artery is obtained. Once the magnitude of the flux is known, an analytical model for the computation of hemoglobin concentration using an MPG can be derived. Using the analytical model the hemoglobin concentration can be predicted with better accuracy.

TABLE III STATISTICAL ANALYSIS (T -TEST)

Paired two sample t-test		
	X	y
Mean	0.646	13.75
Variance	6.9 E-3	2.46
Observations	10	10
Pearson Correlation	0.987	
Hypothesized Mean Difference	0	
df	9	
t Stat	-27.878	
P(T ≤ t) one-tail	2.39 E-10	
t Critical one-tail	1.833	
P(T ≤ t) two-tail	4.78 E-10	
t Critical two-tail	2.26	

V. COINCLUSION

It has been demonstrated that using a magnetic-plethysmogram (MPG), hemoglobin concentration in arterial blood can be evaluated. Since MPG is a non-invasive method, the method of ascertaining the concentration of hemoglobin proposed here is also non-invasive. Results of the limited clinical study on just 10 volunteers presented here, though do not provide clinical validation, but indicates that it is indeed possible to evaluate hemoglobin concentration using the MPG.

The proposed method of measuring haemoglobin concentration utilizing MPG provides better results compared to the method based on the photoplethysmography [16] – [18].

It should be noted here that the sodium lauryl sulfate (SLS) method of measurement of concentration of hemoglobin, which is a very popular method and is in use all over the globe itself has an error of $\pm 15\,\%$ [4]. Thus the $< \pm 7\,\%$ deviations obtained from the limited clinical study is comparable to the ones that are in practice today. The results of the proffered method provides an encouraging sign for further research in this direction. Further clinical validation study is necessary with increased number of volunteers / patients to obtain a clinically relevant measurement of hemoglobin using an MPG.

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