



IJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 Issue: V Month of publication: May 2019

DOI: <https://doi.org/10.22214/ijraset.2019.5018>

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Development of Multi Modal System for Extraction of SpO₂ from Photoplethysmographic Waveforms

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Abstract: *The Non-invasive remote physiological monitoring of soldiers on the battlefield has the potential to provide fast, accurate status assessments that are key to improving the survivability from critical injuries. The development of WPI's wearable wireless pulse oximeter, designed for field-based applications, allowed for the optimization of important hardware features such as physical size and power management. However, software-based digital signal processing (DSP) methods are also required to perform physiological assessments. This research evaluated DSP methods that were capable of providing arterial oxygen saturation (SpO₂) measurements derived from data acquired using a single optical sensor. In vivo experiments were conducted to evaluate the accuracies of the processing methods across ranges of physiological conditions*

Keywords: *Arterial oxygen saturation, Photoplethysmographic, digital signal processing.*

I. INTRODUCTION

It is critical to promptly acquire proper diagnosis and effective treatment in order to optimize a patient's chance of survival. In most situations, however, timely and efficient medical care is not available. Such, telemedicine applications have long been at the forefront of military research in an effort to improve the medical care received by casualties on the frontline. In recent years, the military has been working on a Warfighter Physiological Status Monitor (WPSM) that will allow combat medics to monitor the physiological status of their soldiers, thereby potentially reducing medical response times and improving remote triage capabilities.

A popular method of patient monitoring is pulse oximetry, due to its non-invasive nature. An additional benefit of this modality is the extensive amount of physiological information available through its use. While arterial oxygen saturation (SpO₂) measure typically provided by pulse oximeters. However, despite advances in the hardware optimization, the digital signal processing (DSP) methods required to perform such physiological measurements must still be developed for custom-designed devices.

In order to facilitate the development of a wearable medical monitoring system, the research performed here covered the first step in producing a software package capable of performing multiple physiological measurements based on pulse oximetry sensor data. Specifically, SpO₂ measurements were examined since they were known to provide critical patient information during medical diagnoses. This Paper begins by discussing the needs of field medics and the potential impact of implementing a wearable monitoring system which is used in field-based applications. Current and developing technologies in this research area are covered first, followed by an examination of the fundamental techniques for extracting physiological measurements from photoplethysmographic (PPG) waveforms.

II. RESEARCH OBJECTIVES

While steady progress has been made in the development of an optimized the hardware structure for a wearable pulse oximeter, limitations in commercially available software solutions still exist. The processing software employed by manufacturers to perform physiological measurements can be expensive, proprietary, and does not provide all the measurement features desired in a wearable pulse oximeter. As a result, the newly-developed hardware platform designed at WPI requires custom-developed software routines to perform physiological measurements based on sensor data. Therefore, the goal of this research was the development of a library of software-based processing methods that could be employed to advance the development of the WPI wearable pulse oximeter that is being designed for military and mass casualty applications. The specific research objective were to.

1) *Objective:* Evaluate and characterize a set of software-based processing methods capable of measuring SpO₂ based on a set of PPG signals.

III. THE PHOTOPLETHYSMOGRAPHIC SIGNAL

PPG signals are commonly used in medical settings to obtain vital physiological information. These waveforms, recorded using optical sensors, contain information pertaining to such factors as blood oxygen content, cardiovascular activity, and respiratory patterns. Typically, PPG signals are recorded and analyzed by pulse oximeters to provide SpO₂ measurements. Plethysmographic waveforms represent changes in blood volume in a given region of tissue. Optical sensors are commonly employed as a practical

way of obtaining these waveforms through non-invasive means. Such optical sensors consist of a light source, typically a light-emitting diode (LED), and a photodetector (PD) element. The light source is used to illuminate a region of tissue and the PD measures the amount of light exiting the tissue at a different location.

Most illuminated constituents, such as bone, muscle, venous blood, and various other cellular structures, absorb a constant amount of light, since their volumes and densities do not change over short periods of time. The volume of the arterial blood, however, is modulated by the beating of the heart. Each time the heart contracts, an additional bolus of blood is forced through the arterial pathways. With this variation in arterial volume comes a proportional variation in light absorption that can be measured by an optical sensor. An increase in arterial blood volume causes a corresponding decrease in the amount of light that reaches the PD. The amount of light absorbed by the tissues contains two significant aspects, as shown in Figure. The first is the constant absorbance, or DC component, influenced by the nonvascular tissues and residual arterial and venous blood volumes. The second is a modulated absorbance, or AC component, caused by the variations in arterial blood volume. Together, they affect the amount of light that illuminates the PD to produce a pulsatile waveform, as shown in Figure.

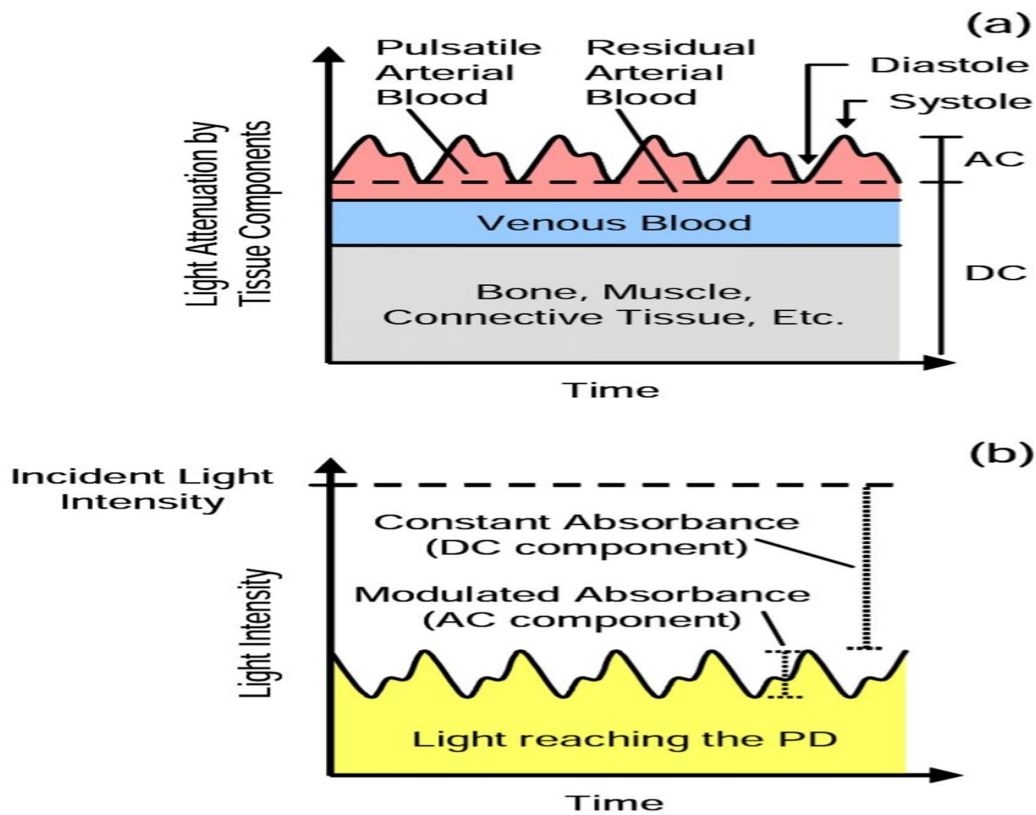


Figure 3.1. Graphical representations of (a) the light absorbance of tissue components and (b) the resulting light intensity illuminating the PD

IV. THEORY OF SpO2 MEASUREMENT

Injuries sustained in a combat environment often directly affect a soldier's cardiac and pulmonary systems, many times causing blood loss, hemothorax, pneumothorax, and other dangerous conditions. Such conditions can lead to hypoxemia, depriving vital organs of oxygen and endangering the casualty's life. SpO2 measurements are routinely employed to detect these hypoxic events before irreversible damage is caused to tissues and organs.

A. Hemoglobin Light Attenuation:

Noninvasive optical estimation of arterial oxygen saturation (SaO2) by pulse oximetry is based on the light absorption properties of blood. Deoxyhemoglobin (Hb), which carries approximately 98% of the blood's oxygen supply, changes its light absorption characteristics when it binds with oxygen. Pulse oximetry exploits this optical difference between Hb and oxygenated hemoglobin (HbO2) to estimate the percentage of arterial blood saturated with oxygen. Hb has a substantially higher absorption profile between

600 and 805 nm, while HbO₂ has a slightly higher absorption profile between 805 and 1000 nm. Wavelengths in the red (R) and infrared (IR) regions around 660 and 900 nm are typically used in most pulse oximetry applications.

Blood with a low amount of oxygen contains an increased level of Hb and a decreased level of HbO₂. As a result, the blood absorbs more light at R wavelengths and less light at IR wavelengths. Conversely, blood with a high amount of oxygen contains a reduced level of Hb and an increased level of HbO₂. The blood then absorbs less light at R wavelengths and more light at IR wavelengths. These wavelength-based absorption characteristics make it possible to measure changes in SaO₂ using optical means.

B. Measurement Derivation

The ratio of R-to-IR light (R/IR) absorbed by arterial blood changes with SaO₂ in an inversely proportional manner, as shown in Figure. As such, Equation 4.1 can be used to approximate this relationship and to calculate SpO₂:

$$SpO_2 = A - B \cdot (R/IR) \dots\dots\dots 4.1$$

where (R/IR) is the ratio of R and IR light absorbed by the arterial blood, A and B are calibration coefficients, and SpO₂ is the estimate of SaO₂.

Equation depicts the equivalent mathematical function:

$$R = (R/IR) = (ACr/DCr) / (ACir/DCir) \dots\dots\dots 4.2$$

where ACr is the AC amplitude of the R signal, DCr is the DC offset of the R signal, ACir is the AC amplitude of the IR signal, DCir is the DC offset of the IR signal, and R is the resulting “ratio-of-ratios”. Combining Equations 4.1 and 4.2 results in Equation 4.3, which estimates SaO₂ based on normalized R and IR PPG signals.

$$SpO_2 = A - B \cdot R \dots\dots\dots 4.3$$

where R is defined by Equation 4.2, A and B are coefficients derived through empirical calibration, and SpO₂ is the resulting estimate of SaO₂.

It should be noted that the relationship between R and SpO₂ is not perfectly linear. However, most clinical work does not require measurements over the full range of SaO₂.

C. SpO₂ Calculation

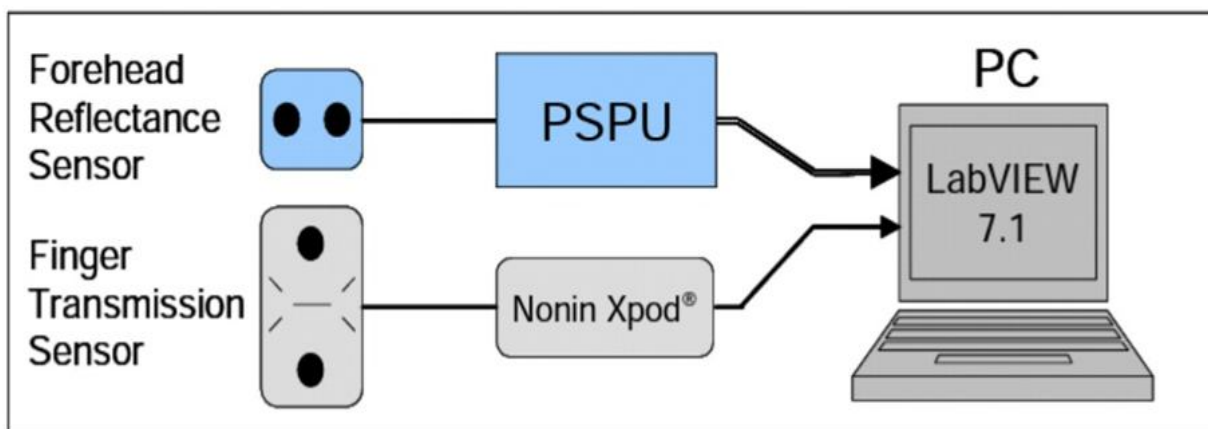
Analysis of PPG signals to determine SpO₂ involved two initial steps: measurement of the DC and AC components. Once these values were obtained from both the R and IR PPGs, the ratio R was calculated using Equation 4.2. The instantaneous R values produced by a given processing method were plotted against corresponding instantaneous reference SpO₂ values obtained from the Nonin Xpod®. The linear regression equation derived from the comparison was used to convert the R values to SpO₂ values, providing the final measurements for the processing method.

V. SpO₂ EXPERIMENTS

R and IR PPG data, as well as reference SpO₂ measurements, were required to assess the accuracy of the SpO₂ processing methods. A series of in vivo experiments were performed to obtain data over a range of SpO₂ values typically monitored for clinical purposes.

A. Experimental Setup

A Nonin Xpod® pulse oximeter was used to obtain reference SpO₂ values from a transmission-mode optical sensor attached to the subject’s index finger since this is the gold standard for monitoring SpO₂ levels. A Nonin reflectance-mode optical sensor was also secured to the subject’s forehead using an elastic headband. This sensor was monitored by the photoplethysmogram signal processing unit (PSPU) which could provide both R and IR waveforms required to perform an SpO₂ measurement. Since the data being recorded consisted of both analog signals and serial data, a LabVIEW program was used to acquire and store the data from both sources simultaneously. Figure 6.1 depicts the experimental setup. Separate AC and DC signals corresponding to the R and IR PPG signals were recorded from the PSPU at a rate of 75 s/s, the sampling rate used by the sensor control routine in WPI’s custom pulse oximeter. Reference SpO₂ values were recorded from the Xpod® once a second



Figur5.1. Experimental setup to acquire SpO2 data.

B. In Vivo Experiments

Data were acquired from 3 healthy male volunteers, ages 24 – 25. During data recording, subjects were seated comfortably in a chair with their arms resting on the armrests. To assess the relationship between reference SpO2 values and measured SpO2 values, each subject was instructed to perform a breath-holding maneuver to induce a noticeable drop in SpO2. A 20 second baseline reading was recorded while each subject was breathing spontaneously. Following the baseline recording, each subject was instructed to hyperventilate for about 15 seconds, and then hold his breath for as long as possible to induce hypoxemia. Following the breath-holding period, each subject resumed spontaneous breathing for 20 seconds to allow the SpO2 readings to return to normal. SpO2 values were monitored during each pause in breathing to ensure that a drop in the oxygen level was noticeable. If a significant drop in SpO2 was not induced, the data were discarded and the experiment was repeated. A total of three successful data sets were recorded.

VI.DC MEASUREMENTS

Three different processing methods were employed to measure the DC components of PPG signals. The baselines and average offsets of the signals could both be used to estimate these DC values and were used to normalize the AC measurements obtained through other methods.

The first method was a moving average. A 3-second window of the most recent PPG samples was averaged to produce a DC value. This calculation was performed as required by the AC processing methods.

The second method used a LPF to track the DC level of a PPG. The chosen filter was an IIR Butterworth which allowed for a reduced number of coefficients compared to FIR filters and a smooth passband with no significant ripple. A cutoff of 0.1 Hz was used to remove the high-frequency pulsatile component generated by cardiac activity. A 5th order filter was required to maintain stability.

The third processing method followed the baseline of the PPG. The minimum value in a 3-second window of the most recent PPG samples was used as a DC value. This calculation was performed as required by the AC processing methods.

A. AC Measurements

Two different processing methods were employed to measure the pulsatile amplitudes of the R and IR PPGs. Once measured, the AC values were normalized using the results obtained from the above DC measurements. The normalized AC measurements were used to calculate R values which were converted to SpO2 values based on the empirical relationship between R and SpO2.

1) *PPG Differentials*: Using differentials to estimate AC amplitude first involved calculating the absolute derivative of a PPG, as demonstrated in Figure 6.1 During a single analysis, 3 seconds of the absolute derivative were averaged to produce an AC measurement. AC values from R and IR PPGs were normalized with their respective DC values and used to calculate the R values. To assess method accuracy, the calculated R values were converted to SpO2 measurements and plotted against corresponding reference SpO2 values, as shown in Figures .

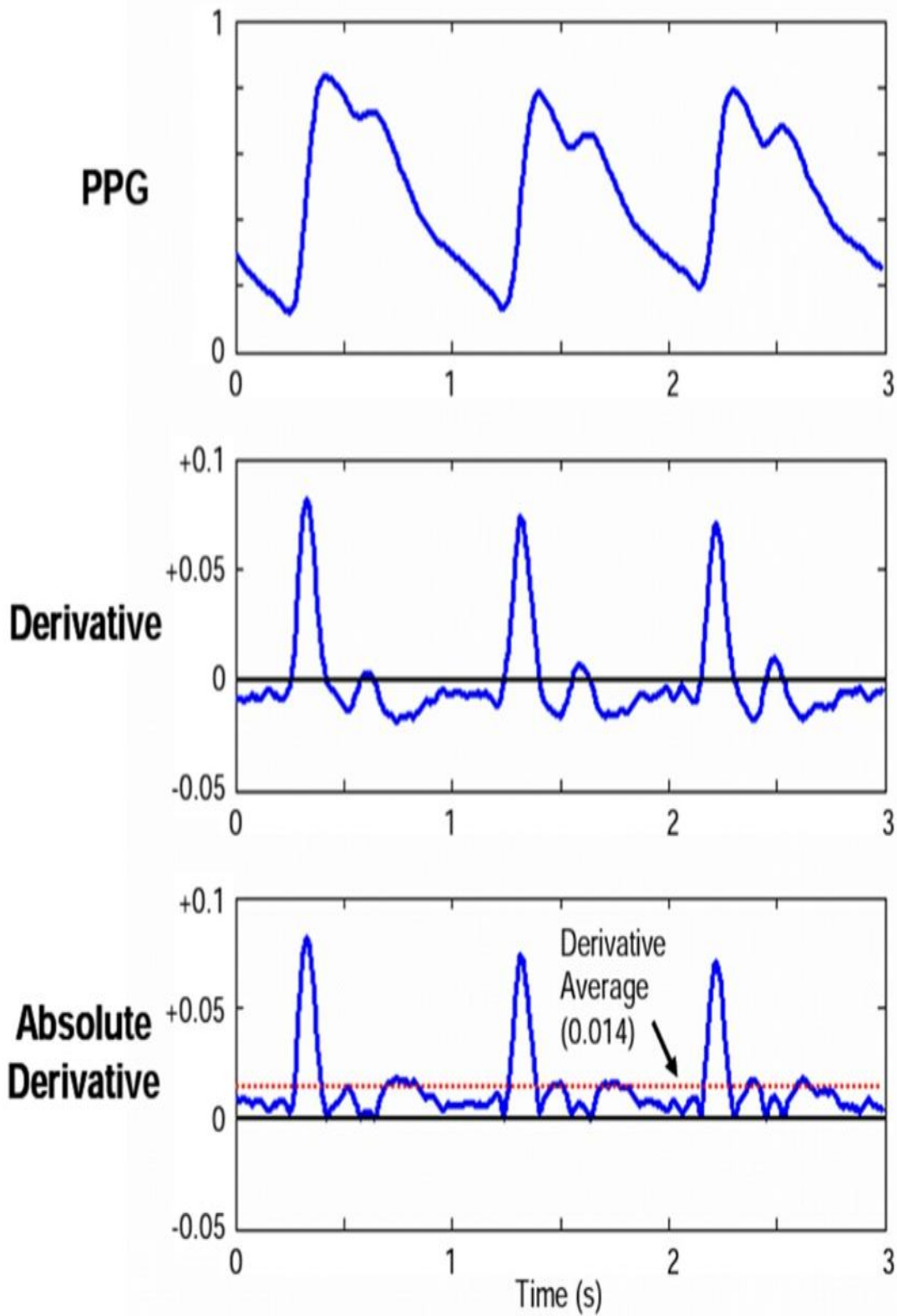


Figure 6.1. Relative PPG with corresponding derivative and absolute derivative. The marked derivative average is used as an AC value.

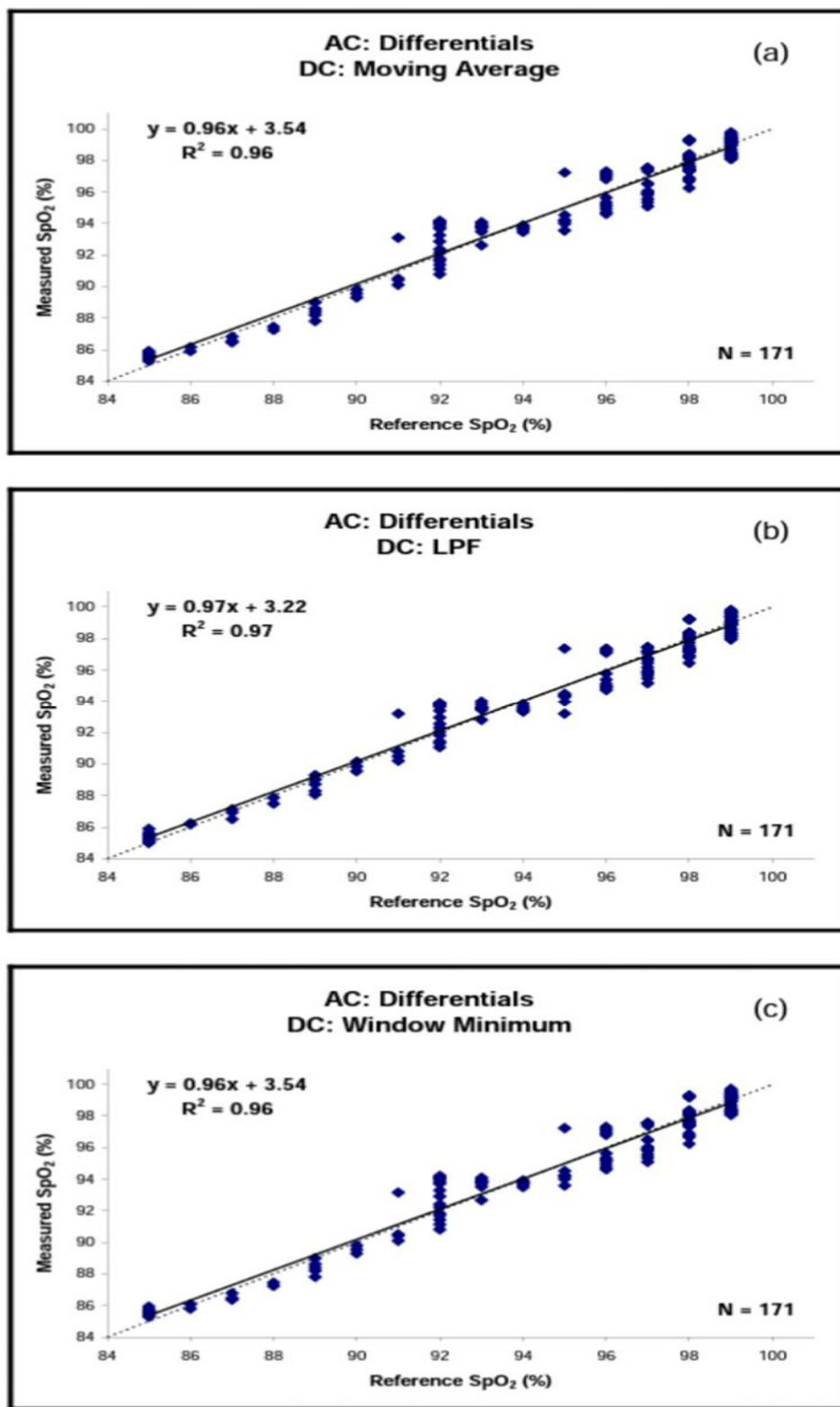


Figure 6.2. SpO2 measurements based on PPG differentials normalized using (a) a moving average, (b) LPF, and (c) window minimum. Regression lines (—) and lines of identity (---) are shown for comparison.

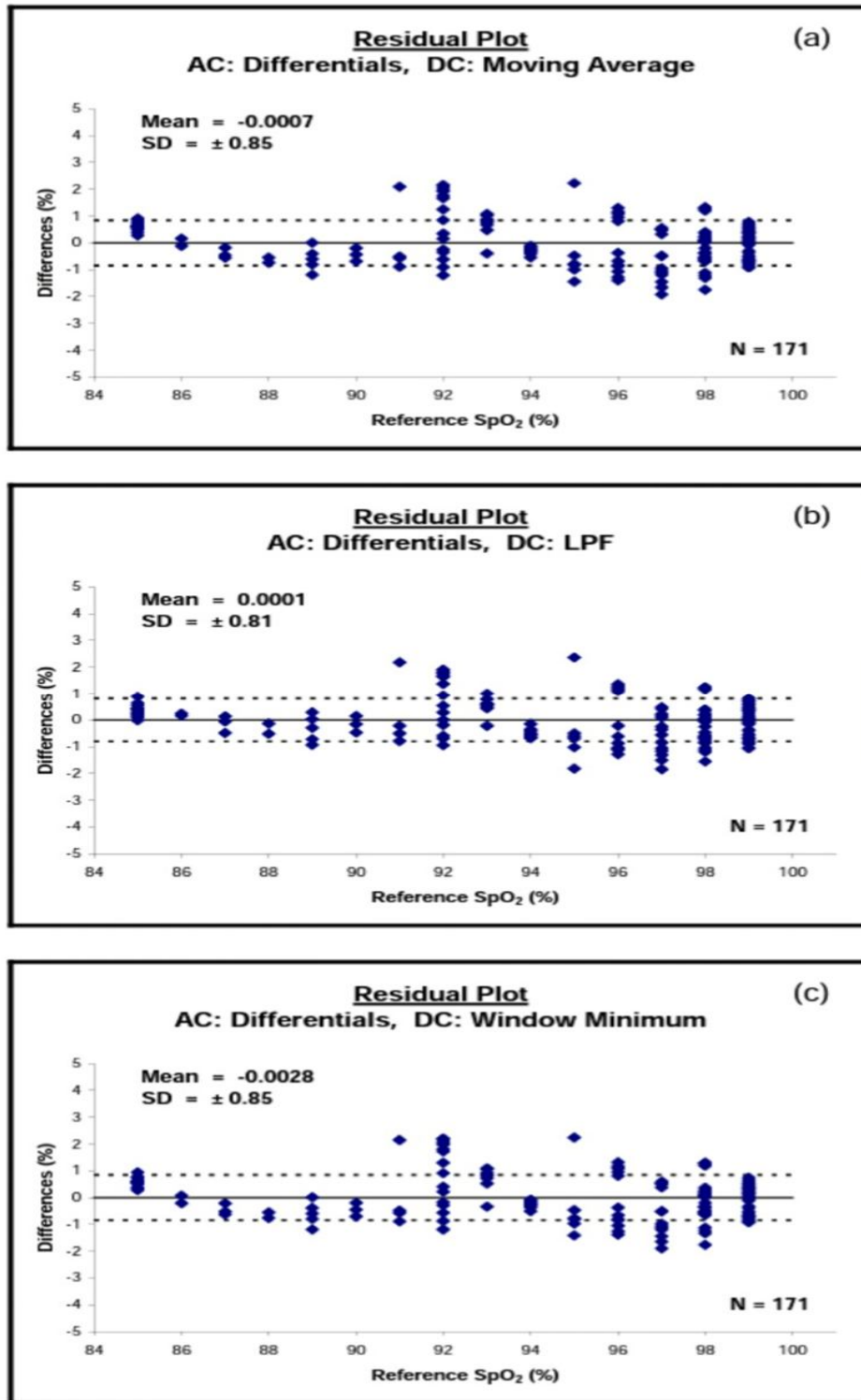


Figure 6.3. Residual data plots from SpO₂ measurements based on PPG differentials normalized using (a) a moving average, (b) LPF, and (c) window minimum.

AC Measurements	DC Measurements	R ² Value	Bias (%)	SEE (%)
Differentials	Moving Average	0.96	-0.0007	0.84
	LPF	0.97	0.0001	0.82
	Window Minimum	0.96	-0.0028	0.91

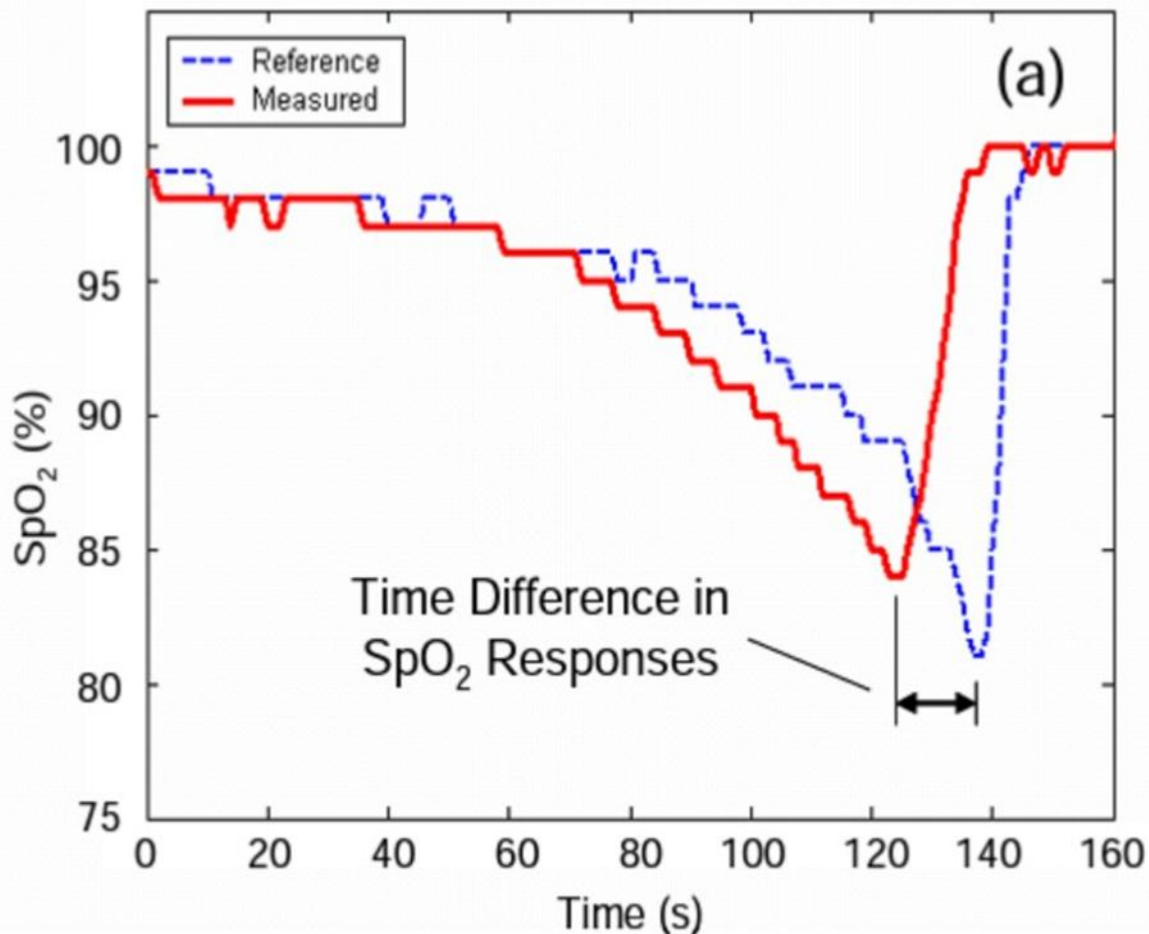
Table 6.4. Assessment results for SpO2 processing methods.

VII. SpO2 ASSESSMENT

A. Measurement Response Times

During assessment of the SpO2 processing methods, a difference in the response times was noted when comparing the SpO2 values provided by the processing methods to those obtained from the reference oximeter. As shown in Figure a, comparable drops in SpO2 were registered between 5 and 20 seconds apart by the reference source and all the processing methods. This shift was attributed to two factors: differences in sensor locations and differences in processing technique.

Reference readings were obtained from a sensor attached to the finger while the processing methods assessed signals recorded from a sensor mounted on the forehead. Due to differences in the circulation between the heart and the two sensor sites, drops in SpO2 occur earlier at the forehead compared to the fingertip due to differences in circulation transport.



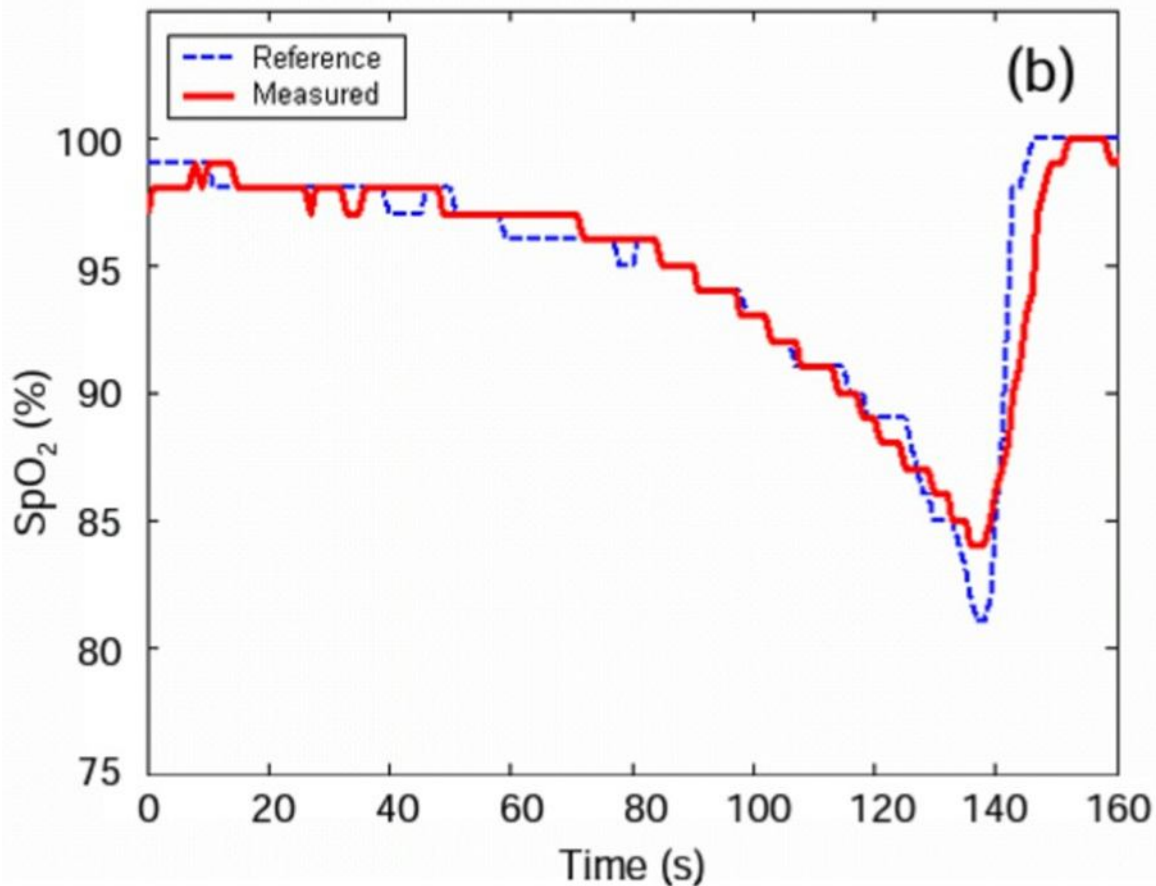


Figure 7.1. Measured and reference SpO₂ values (a) as they are normally obtained in relation to each other and (b) after aligning the drops in SpO₂.

VIII. CONCLUSIONS

Acquiring accurate physiological measurements from patients is vital to providing effective triage and medical care in the field. As a result, the proper selection of a set of accurate processing methods is paramount in the development of a wearable medical device designed for field-based applications. This research evaluated different processing methods as a means of performing multiple physiological measurements based on a single set of photoplethysmograms acquired by a non-invasive wearable pulse oximeter.

Arterial oxygen saturation were assessed in this research since these measurements provide vital physiological information to caregivers during medical evaluations. A series of in vivo experiments were conducted to record photoplethysmographic waveforms and corresponding reference values measure. The data were then used to characterize the accuracies of the processing methods evaluate during the study.

Since a number of resulting data trends between sets of measured and reference values did not always appear to be linear, alternative regression equations were applied to the data sets to determine what form of equation best estimated the data's relationship.

Although the miniaturized wearable pulse oximeter developed in our lab has been optimized for physical size and power, further evaluations must be conducted to understand the limitations of each signal processing method in terms of suitability for implementation in a microcontroller environment.

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