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Measurement Site and Photodetector Size Considerations in Optimizing Power Consumption of a Wearable Reflectance Pulse Oximeter

Y. Mendelson, Ph.D., C. Pujary, B.E.
Department of Biomedical Engineering, and Bioengineering Institute
Worcester Polytechnic Institute, Worcester, MA 01609, USA

Abstract– **Site selection and power consumption play a crucial role in optimizing the design of a wearable pulse oximeter for long-term telemedicine application. In this study we investigated the potential power saving in the design of a reflectance pulse oximeter taking into consideration measurement site and sensor configuration. *In-vivo* experiments suggest that battery longevity could be extended considerably by employing a wide annularly shaped photodetector ring configuration and performing SpO_2 measurements from the forehead region.**

Keywords– **pulse oximeter, wearable sensors, telemedicine**

I. Introduction

Noninvasive pulse oximetry is a widely accepted method for monitoring arterial hemoglobin oxygen saturation (SpO_2). Oxygen saturation is an important physiological variable since insufficient oxygen supply to vital organs can quickly lead to irreversible brain damage or result in death.

Pulse oximetry is based on spectrophotometric measurements of changes in blood color. The method relies on the detection of a photoplethysmographic (PPG) signal produced by variations in the quantity of arterial blood associated with periodic cardiac contraction and relaxation.

Pulse oximeter sensors are comprised of light emitting diodes (LEDs) and a silicon photodetector (PD). Typically, a red (R) LED with a peak emission wavelength around 660 nm, and an infrared (IR) LED with a peak emission wavelength around 940 nm are used as light sources. SpO_2 values are derived based on an empirically calibrated function by which the time-varying (AC) signal component of the PPG at each wavelength is divided by the corresponding time-invariant (DC) component which is due to light absorption and scattering by bloodless tissue, residual arterial blood volume during diastole, and non-pulsatile venous blood.

SpO_2 measurements can be performed in either transmission or reflection modes. In transmission mode, the sensor is usually attached across a fingertip or earlobe such that the LEDs and PD are placed on opposite sides of a pulsating vascular bed. Alternatively, in reflection pulse oximetry, the LEDs and PD are both mounted side-by-side facing the same side of the vascular bed. This configuration enables measurements from multiple locations on the body where transmission measurements are not feasible.

Backscattered light intensity can vary significantly between different anatomical locations. For example, optical reflectance from the forehead region is typically strong because of the relatively thin skin covering the skull combined with a higher density of blood vessels. On the contrary, other anatomical locations, such as the limbs or torso, have a much lower density of blood vessels and, in addition, lack a dominant skeletal structure in close proximity to the skin that helps to reflect some of the incident light. Therefore, the AC components of the reflected PPGs from these body locations are considerably smaller. Consequently, it is more difficult to perform accurate pulse oximetry measurement from these body locations without enhancing cutaneous circulation using artificial vasodilatation.

Sensors used with commercial transmission or reflection pulse oximeters employ a single PD element, typically with an active area of about 12-15mm^2. Normally, a relatively small PD chip is adequate for measuring strong transmission PPGs since most of the light emitted from the LEDs is diffused by the skin and subcutaneous tissues predominantly in a forward-scattering direction. However, in reflection mode, only a small fraction of the incident light is backscattered by the subcutaneous layers. Additionally, the backscattered light intensity reaching the skin surface is normally distributed over a relatively large area surrounding the LEDs. Hence, the design of a reflectance-mode pulse oximeter depends on the ability to fabricate a sensor that has improved sensitivity and can detect sufficiently strong PPGs from various locations on the body combined with sophisticated digital signal algorithms to process the relatively weak and often noisy signals.

To improve the accuracy and reliability of reflection pulse oximeters, several sensor designs have been described based on a radial arrangement of discrete PDs or LEDs. For example, Mendelson *et al* [1]-[2] and Konig *et al* [3] addressed the aspect of unfavorable SNR by developing a reflectance sensor prototype consisting of multiple discrete PDs mounted symmetrically around a pair of R and IR LEDs. Takatani *et al* [4]-[5] described a different sensor configuration based on 10 LEDs arranged symmetrically around a single PD chip.

The U.S. military has long been interested in combining noninvasive physiological sensors with wireless communication and global positioning to monitor soldier's vital signs in real-time. Similarly, remote monitoring of a person's health status who is located in a dangerous environment, such as mountain climbers or divers, could be beneficial. However, to gain better acceptability and address the unmet demand for long term continuous monitoring, several technical issues must be solved in order to design more compact sensors and instrumentation that are power

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efficient, low-weight, reliable and comfortable to wear before they could be used routinely in remote monitoring applications. For instance, real-time continuous physiological monitoring from soldiers during combat using existing pulse oximeters is unsuitable because commercial oximeters involve unwieldy wires connected to the sensor, and sensor attachment to a fingertip restrains normal activity. Therefore, there is a need to develop a battery-efficient pulse oximeter that could monitor oxygen saturation and heart rate noninvasively from other locations on the body besides the fingertips.

To meet future needs, low power management without compromising signal quality becomes a key requirement in optimizing the design of a wearable pulse oximeter. However, high brightness LEDs commonly used in pulse oximeters requires relatively high current pulses, typically in the range between 100-200mA. Thus, minimizing the drive currents supplied to the LEDs would contribute considerably toward the overall power saving in the design of a more efficient pulse oximeter, particularly in wearable wireless applications. In previous studies we showed that the driving currents supplied to the LEDs in a reflection and transmission pulse oximeter sensors could be lowered significantly without compromising the quality of the PPGs by increasing the overall size of the PD [6]-[8]. Hence, by maximizing the light collected by the sensor, a very low power-consuming sensor could be developed, thereby extending the overall battery life of a pulse oximeter intended for telemedicine applications. In this paper we investigate the power savings achieved by widening the overall active area of the PD and comparing the LEDs driving currents required to produce acceptable PPG signals from the wrist and forehead regions as two examples of convenient body locations for monitoring SpO_2 utilizing a prototype reflectance pulse oximeter.

II. METHODOLOGY

A. Experimental setup

To study the potential power savings, we constructed a prototype reflectance sensor comprising twelve identical Silicon PD chips (active chip area: 2mm x 3mm) and a pair of R and IR LEDs. As shown schematically in Fig. 1, six PDs were positioned in a close inner-ring configuration at a radial distance of 6.0mm from the LEDs. The second set of six PDs spaced equally along an outer-ring, separated from the LEDs by a radius of 10.0mm. Each cluster of six PDs were wired in parallel and connected through a central hub to the common summing input of a current-to-voltage converter. The analog signals from the common current-to-voltage converter were subsequently separated into AC and DC components by signal conditioning circuitry. The analog signal components were then digitized at a 50Hz rate for 30 seconds intervals using a National Instruments DAQ card installed in a PC under the control of a virtual instrument implemented using LabVIEW 6.0 software.

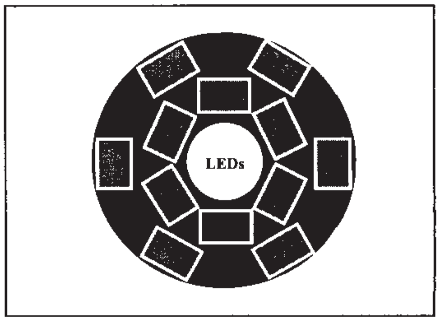

Fig. 1. Prototype reflectance sensor configuration showing the relative positions of the rectangular-shaped PDs and the LEDs.

B. In Vivo Experiments

A series of *in vivo* experiments were performed to quantify and compare the PPG magnitudes measured by the two sets of six PDs. The prototype sensor was mounted on the dorsal side of the wrist or the center of the forehead below the hairline. These representative regions were selected as two target locations for the development of a wearable telesensor because they provide a flat surface for mounting a reflectance sensor which for example could be incorporated into a wrist watch device or attached to a soldier's helmet without using a double-sided adhesive tape. After the sensor was securely attached, the minimum peak currents flowing through each LED was adjusted while the output of the amplifier was monitored continuously to assure that distinguishable and stable PPGs were observed from each set of PDs and the electronics were not saturated.

Two sets of measurements were acquired from each body location. In the first set of experiments we kept the currents supplied to the LEDs at a constant level and the magnitude of the PPGs measured from each set of six PDs were compared. To estimate the minimum peak currents required to drive the LEDs for the near and far-positioned PDs, we performed a second series of measurements where the driving currents were adjusted until the amplitude of the respective PPG reached approximately a constant amplitude.

III. RESULTS

Typical examples of reflected PPG signals measured by the inner set of six PDs from the forehead and wrist for a constant peak LED current (R: 8.5mA, IR: 4.2mA) are plotted respectively in Fig. 2.

The relative RMS amplitudes of the PPG signals measured by the six near (N) and far (F) PDs, and the combination of all 12 PDs (N+F) are plotted in Fig. 3(a) and 3(b) for a peak R LED drive current of 8.5mA and a peak IR LED drive current of 4.2mA, respectively. Analysis of the data revealed that there is a considerable difference between the signals measured by each set of PDs and amplitude of the respective PPG signals depends on measurement site.

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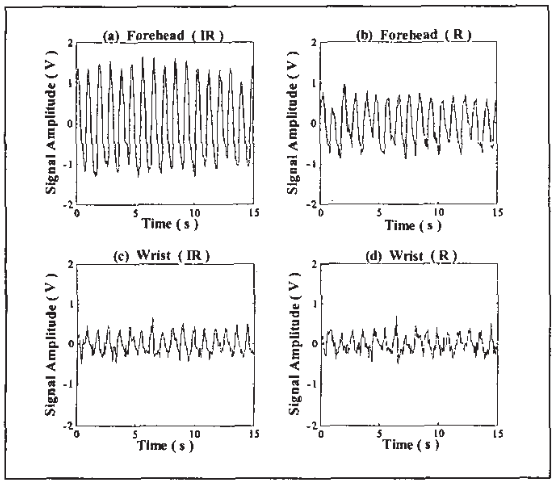

Fig. 2. Raw PPG signals measured from the forehead (*a* and *b*) and wrist (*c* and *d*) for constant LED driving currents.

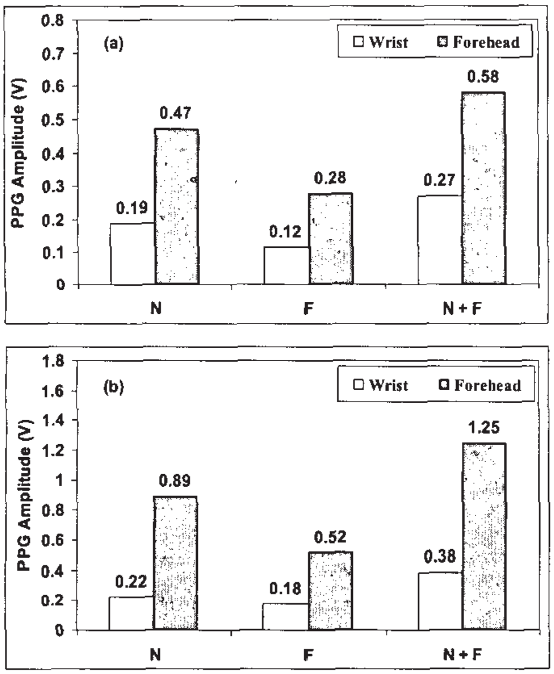

Fig. 3. PPG signal amplitudes measured by the near (N), far (F) and combination (N+F) PDs from the wrist and forehead for constant R and IR LED drive currents corresponding to 8.5mA (*a*) and 4.2mA (*b*), respectively.

Fig. 4 compares the relative peak LED currents required to maintain a constant AC RMS amplitude of approximately 0.840(±0.017)V for the N, F and (N+F) PDs measured from the forehead.

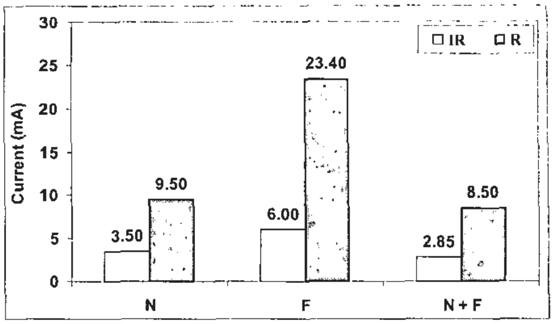

Fig. 4. Relative LED peak driving currents required to maintain a constant PPG amplitude of 0.840V RMS for the near (N), far (F) and combination (N+F) PD configurations. Measurements were obtained from the forehead.

IV. Discussion

The successful design of a practical wearable pulse oximeter presents several unique challenges. In addition to user acceptability, the other most important issues are sensor placement and power consumption. For example, utilizing disposable tape or a reusable spring-loaded device for attachment of pulse oximeter sensors, as commonly practiced in clinical medicine, poses significant limitations, especially in ambulatory applications.

Several studies have shown that oximetry readings may vary significantly according to sensor location. For example, tissue blood volume varies in different parts of the body depending on the number and arrangement of blood vessels near the surface of the skin. Other factors, such as sensor-to-skin contact, can influence the distribution of blood close to the skin surface and consequently can cause erroneous readings. Therefore, to ensure consistent performance, it is important to pay close attention to the design of optical sensors used in reflectance pulse oximetry and the selection of suitable sites for sensor attachment.

The current consumed by the LEDs in a battery powered pulse oximeter is inversely proportional to the battery life. Hence, minimizing the current required to drive the LEDs is a critical design consideration, particularly in optimizing the overall power consumption of a wearable pulse oximeter. However, reduced LED driving currents directly impacts the incident light intensity and, therefore, could lead to deterioration in the quality of the measured PPGs. Consequently, lower LED drive currents could result in unreliable and inaccurate reading by a pulse oximeter.

From the data presented in Fig. 2, it is evident that the amplitude and quality of the recorded PPGs vary significantly between the forehead and the wrist. We also observed that using relatively low peak LED driving currents, we had to apply a considerable amount of external pressure on the sensor in order to measure discernable PPG

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signals from the wrist. In contrast, using minimal contact pressure and similar LED driving currents produced significantly larger and less noisy PPG signals from the forehead. These noticeable differences are due to the lower density of superficial blood vessels on the arms compared to the highly vascular forehead skin combined with a strong light reflection from the forehead bone. Additionally, during conditions of peripheral vasoconstriction, a sensor placed on the forehead can maintain stronger PPGs longer compared to a finger sensor [9].

Despite the noticeable differences between the PPG signals measured from the wrist and forehead, the data plotted in Fig. 3 also revealed that considerable stronger PPGs could be obtained by widening the active area of the PD which helps to collect a bigger proportion of backscattered light intensity. The additional increase, however, depends on the area and relative position of the PD with respect to the LEDs. For example, utilizing the outer-ring configuration, the overall increase in the average amplitudes of the R and IR PPGs measured from the forehead region was 23% and 40%, respectively. Similarly, the same increase in PD area produced an increase in the PPG signals measured from the wrist, but with a proportional higher increase of 42% and 73%.

The data presented in Fig. 4 confirmed that in order to produce constant PPG amplitudes, significantly higher currents are required to drive the LEDs when backscattered light is measured by the outer PD set compared to the inner set. This observation was expected since the backscattered light intensity measured is inversely related to the separation distance between the PD and the LEDs [10]. In comparing the three different PD configurations, we found that by combining both PD sets to simulate a single large PD area, it is possible to further reduce the driving currents of the LEDs without compromising the amplitude or quality of the detected PPGs.

Lastly, we used the LED peak driving currents plotted in Fig. 4 to estimate the expected battery life of a typical 220mAh Lithium coin size battery assuming that a similar battery is used to power the optical components of a wearable pulse oximeter. Table 1 summarizes the estimated battery life for the different PD configurations tested in this study. The calculations are based on LEDs pulsed continuously at a typical duty cycle of approximately 1.5%.

Table 1. Comparison of estimated battery life for different PD configurations. Values based on forehead measurements for a typical 220mAhr coin size battery.

PD CONFIGURATION	BATTERY LIFE [Days]
Near	45.8
Far	20.3
Near+Far	52.5

Note that the estimated values given in Table 1 are very conservative since they rely only on the power consumed by the LEDs without taking into consideration the additional power demand imposed by other components of a wearable pulse oximeter. Nevertheless, the considerable differences in the estimated power consumptions clearly points out the practical advantage gained by using a reflection sensor comprising a large ring-shaped PD area to perform SpO_2 measurements from the forehead region.

V. Conclusion

Site selection and LED driving currents are critical design consideration in optimizing the overall power consumption of a wearable battery-operated reflectance pulse oximeter. In this study we investigated the potential power saving in a ring-shaped sensor configuration comprising two sets of photodetectors arranged in a concentric ring configuration. *In-vivo* experiments revealed that battery longevity could be extended considerably by employing a wide annular PD and limiting SpO_2 measurements to the forehead region.

Acknowledgment

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