MINIMIZATION OF LED POWER CONSUMPTION IN THE DESIGN OF A WEARABLE PULSE OXIMETER
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ABSTRACT– Power budgeting is a critical consideration in designing a wearable pulse oximeter for long-term telemedicine application. This paper investigates the potential power saving in a ring-shaped sensor configuration comprising multiple photodetector elements positioned in transmission, transflection and reflection modes. Preliminary in vivo experiments revealed that battery longevity could be extended considerably by employing reflection rather than transflection or transmission mode measurements.

KEY WORDS – wearable sensors, pulse oximeter, telemedicine

INTRODUCTION

Pulse oximetry is a widely accepted method for noninvasive monitoring of arterial oxygen saturation. Oxygen saturation is a crucial indicator of oxygen supply and is therefore an important physiological variable since insufficient supply of oxygen to vital organs can quickly lead to irreversible brain damage or result in death.

Oximetry is based on spectrophotometric measurements of changes in blood color. Optical property of blood in the visible (between 500 and 700nm) and near-infrared (between 700 and 1000nm) spectral regions depends strongly on the amount of oxygen carried by blood. The method exploits the fact that reduced hemoglobin, or deoxyhemoglobin (Hb), has a higher optical extinction in the red region of the spectrum around 660nm compared with oxygenated hemoglobin, or oxyhemoglobin (HbO2). On the other hand, in the near-infrared region of the spectrum around 940nm, the optical absorption by Hb is lower compared to HbO2.

Pulse oximetry relies on the detection of a photoplethysmographic (PPG) signal produced by variations in the quantity of arterial blood associated with periodic contractions and relaxations of the heart. The magnitude of this signal depends on the amount of blood ejected from the heart with each systolic cycle, the optical absorption of blood, absorption by skin and tissue components, and the specific wavelengths used to illuminate the vascular tissue bed.

Noninvasive optical sensors for measuring arterial oxyhemoglobin saturation by a pulse oximeter (termed $S_p{O}_2$) are comprised of a pair of small and inexpensive light emitting diodes (LEDs) and a highly sensitive silicon photodetector (PD). Typically, a red (R) LED centered on a peak emission wavelength around 660 nm and an infrared (IR) LED centered on a peak emission wavelength around 940 nm are used as light sources. $S_p{O}_2$ is derived by computing the relative magnitudes of the R and IR PPGs. Electronic circuits inside the pulse oximeter separate the R and IR PPGs into their respective cardiac-synchronized pulsatile (AC) and non-pulsatile (DC) signal components. An algorithm performs a mathematical normalization by which the time-varying AC signal at each wavelength is divided by the corresponding time-invariant DC component which results mainly from the light absorbed and scattered by the bloodless tissue, the residual arterial blood when the heart is in diastole, venous blood and skin pigmentation.

Noninvasive measurement by pulse oximetry can be performed in either transmission or reflection modes. In transmission pulse oximetry, the sensor is usually attached across a fingertip, foot, or earlobe such that the light source and PD are placed on opposite sides of a peripheral pulsating vascular bed. Alternatively, in reflection pulse oximetry, the LEDs and PD are both mounted side-by-side on the same planar surface. This configuration enables measurements from multiple locations on the body where transmission measurements are not feasible. Reflection pulse oximetry has recently become an important new clinical modality with potential benefits in fetal monitoring where the only accessible location is the fetal head.

While transmission and reflection pulse oximetry are based on similar spectrophotometric principles, reflection measurements are in general more challenging to perform. For example, depending on sensor configuration and placement, the pulsatile AC signals in reflection PPGs are generally smaller compared to transmission PPGs. Furthermore, in addition to the dependence on the optical absorption by blood, reflection PPGs can be adversely affected by the interaction of incident light with underlying subcutaneous tissue structures such as bones. Therefore, the accuracy and reliability of reflectance pulse oximetry is essentially dependent on the ability to design a sensor that can detect sufficiently strong reflection PPGs from various locations on the body combined with advanced algorithms to process relatively weak and often noisy PPGs.
Commercially available sensors used with transmission and reflection pulse oximeters employ a single PD element, typically with an active area of about 12-15mm², to measure the light intensity emanating from the skin. Since most of the light emitted from the LEDs is diffused by the skin and subcutaneous tissues, predominantly in a forward-scattering direction, a relatively small PD chip is adequate for measuring strong transmission PPGs. In reflection mode, however, only a small fraction of the incident light is normally backscattered from the skin and the backscattered light is distributed over a region that is concentric with respect to the location of the LEDs. Therefore, the performance of reflectance pulse oximetry using a small PD area could be degraded because of relatively poor signal-to-noise ratio, particularly when measurements are performed from body locations where peripheral perfusion is low and the magnitude of the reflected PPGs is low. This suggests that to measure reflection PPGs with stronger pulsatile components, a larger area PD could be employed in order to capture a greater proportion of the backscattered light intensity.

To improve the accuracy and reliability of reflection pulse oximeters, several improved sensor designs have been described in the literature based on a radially symmetric arrangement of discrete PDs or LEDs. For example, Mendelson et al [1-3] and Konig et al [4] found that significant improvements in signal-to-noise ratio could be achieved by increasing the active area of the PD and optimizing the separation distance between the LEDs and the PD. Takatani and co-workers described a different sensor configuration based on eight [5] or ten [6] symmetrically arranged LEDs surrounding a single PD chip.

Initially, pulse oximetry was limited to stationary in-hospital use on motionless patients undergoing surgery. During the past few years, several companies developed small pulse oximeters, some including data transmission via telemetry, to expand the applications of pulse oximeters. For example, battery-operated pulse oximeters are now attached to patients during emergency transport as they are being moved from a remote location to a hospital or between hospital wards.

Companies offering smaller units with improved filtering of noisy signals are now suggesting that pulse oximetry could be used effectively outside hospitals in areas where patient movement has traditionally posed an insurmountable barrier to use. The application of advanced telecommunications technology to long-term home care of the elderly, including patients with congestive heart failure, chronic cyanotic pulmonary diseases, chronic wound care, permanent disability and terminal illnesses, is also a rapidly growing segment of the health care industry. The health care and particularly home care industry is continuously seeking to reduce some of the inefficiencies of home health care by replacing nursing visits with remote collection of vital physiological information. By using state-of-the-art medical diagnosis capable of remote monitoring, health care providers who might be located miles from a patient’s home can conduct a checkup on a home care patient's vital signs such pulse rates, blood oxygenation and body temperature.

**POTENTIAL MILITARY APPLICATIONS OF PULSE OXIMETRY**

The U.S. military has long been interested in incorporating hand-held pocket-sized personal digital assistant (PDA) computers and a Warefighter Personnel Status Monitor (WPSM) into its telemedicine applications for improved combat casualty care. By combining noninvasive physiological sensors with innovative microelectronics, a wireless communication link, and global positioning, the WPSM could monitor the soldier’s vital signs in real-time. It is envisioned that in the near future a frontline medic would be able to utilize this technology to read a soldier’s medical history and assess the soldier’s status on the battlefield using advanced biomedical sensors. This technology could be used not only to improve far-forward diagnosis and treatment of combat casualties (i.e. performing remote triage), but also to predict the physiological performance of healthy soldiers or the likelihood of potential serious medical consequences that could be developed if certain medical conditions are left undetected or untreated. 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 efficient, lightweight, reliable and comfortable to wear before they could be used routinely by soldiers as part of their normal combat uniform.

Despite the steady progress in the miniaturization of pulse oximeters, to date, the most significant limitation is battery longevity and telemetric communication. For instance, real-time continuous physiological monitoring from soldiers during combat using existing pulse oximeters is unsuitable, particularly on mobile soldiers, because commercial oximeters involve unwieldy wires connected to the sensor and sensor attachment to the fingers restrain normal activity. Therefore, there is a need to develop a more advanced battery-efficient pulse oximeter that could monitor oxygen saturation and heart rate noninvasively from other locations on the body besides the fingertips.

**POWER MINIMIZATION IN PULSE OXIMETRY**

High brightness LEDs are the preferred light sources commonly used in pulse oximeters. To obtain the high light intensity required to overcome the strong optical
absorption by blood and tissue, these LEDs require relatively high current pulses, typically in the range between 100-200mA. Hence, the LEDs consume a large portion of the power in a battery-operated pulse oximeter. Therefore, 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.

It should be noted that the LEDs in a pulse oximeter are alternately switched on and off by high-speed digital circuitry in order to allow synchronized detection of the light by a single photodetector. Synchronizing the detection reduces the on time of each LED, and thereby helps to reduce the overall power consumption. In addition to lowering the duty cycle of the LEDs, to ensure low power consumption, it is also possible to lower the average driving currents of the LEDs. Lowering the intensity of the LEDs, however, could lead to significant deteriorations in the overall signal-to-noise ratio. As a result of this design tradeoff, measurements could become more susceptible to external interferences and thus could affect the overall accuracy and reliability of the readings.

Besides lowering the duty cycle and average driving currents supplied to the LEDs, the conventional approach for reducing power consumption in portable electronics, such as in calculators and notebook PCs is to temporarily disable non essential circuitry when the device is not in use over a certain period of time. However, while sleep-mode power reduction techniques are appropriate for consumer electronics, this specific approach may not be acceptable in certain medical applications. For example, heart rate and oxygen saturation readings by a pulse oximeter are used to monitor potential dangerous trends in the physiological status of a patient and changes in oxygen saturation can occur in a relatively short time span. Moreover, the readings of a pulse oximeter are based on a time averaging technique and, therefore, pulse oximeters require a few seconds of stable input signals before they can process and display accurate and reliable physiological information. Hence, by switching the oximeter on and off intermittently to conserve power, critical clinical information may be compromised or lost.

**WEARABLE PULSE OXIMETRY**

With the advent of custom ASIC technology, there has been a great deal of interest in the development of miniature pulse oximeters. One example of a miniature device is the Onyx 9500 pulse oximeter (NONIN Medical, Inc.). To date, this device is the world’s smallest self-contained finger pulse oximeter. Its low price, compact size, low weight (2 oz with batteries) and low power requirements (two 1.5V AAA-size batteries) provide a very cost effective solution for spot checks and short-term monitoring. Practically, however, the requirement that the device must be attached to the fingertip imposes restrictions on hand motions and thus limits its use for long-term applications. Further miniaturization and integration of a pulse oximeter with wireless communication and has been described by Crilly et al [7]. Rhee et al [8] developed a miniaturized double-ring sensor intended for long-term continuous monitoring of SpO2 and heart rate from the base of a finger utilizing wireless reflection pulse oximetry. The idea to design a pulse oximeter sensor based on a ring-shaped configuration was motivated by the need to develop a comfortable wearable device for the aging population that the majority of people will accept to wear for an extended period of time. Additionally, utilizing a ring configuration approach has a unique feature since the sensor can be securely attached to the body without the need to use a disposable adhesive tape normally used to affix reflectance type sensors. Although the unique sensor developed by Rhee and co-workers has adequately addressed the issue of susceptibility to motion artifacts by devising a double-ring design, their optical sensor is based on R and IR LEDs positioned adjacent to a single PD chip as is commonly employed in reflection type commercial sensors. Furthermore, Rhee et al did not justify why they chose a reflection mode rather than relying on the more popular transmission mode.

As noted above, low power management without compromising signal quality is a key requirement in optimizing the design of a wearable pulse oximeter. In previous studies we showed that the driving currents supplied to the LEDs in a reflection [9] and transmission [10] pulse oximeter could be lowered significantly without compromising the quality of the PPGs by increasing the overall size of the PD in a planar sensor configuration. 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 compare the LEDs driving currents required to produce acceptable PPG signals in transmission, transflection and reflection modes. The paper focuses specifically on estimating the power consumption of a prototype ring-shaped optical sensor housing multiple PDs for monitoring oxygen saturation and heart rate from the base of a finger.

**METHODOLOGY**

*Experimental setup*

To study the potential power savings associated with different PD positions in a ring-shaped sensor, we constructed and tested a prototype sensor configuration consisting of 6 (3mm x 4mm active area) identical silicon PDs and a pair of R and IR LEDs. The PDs and LEDs were arranged symmetrically along the inner circumference of the sensor. As shown schematically in Fig. 1, two of the six PDs (PD-1 and PD-6) were positioned adjacent to the LEDs, typical of a reflection sensor configured for measuring backscattered light. Two PDs (PD-2 and PD-5) were positioned along a transverse
plane and were used to measure light that is emanating from both sides of the finger in a so-called transflection mode. The remaining PDs (PD-3 and PD-4) were positioned opposite the LEDs to measure the light transmitted through the finger.

As shown schematically in Fig. 2, each PD was wired through a central hub that was connected directly to the common summing input of a current-to-voltage converter. The hub provided a convenient way to connect in parallel two PDs simultaneously for each of the three modes. As is commonly practiced in pulse oximetry, the analog signals from the common current-to-voltage converter were subsequently separated into pulsatile (AC) and non-pulsatile (DC) components by signal conditioning circuitry. The analog signal components were then digitized separately 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.

In Vivo Experiments

A series of in vivo experiments were performed to quantify and compare the magnitudes of the PPGs measured by each pair of PDs in reflectance, transflection or transmission modes. As illustrated schematically in Fig. 3, the prototype sensor was wrapped around the proximal phalanx of a volunteer’s finger with the LEDs resting on the palm side of the index finger. After the sensor was securely attached to the finger, the minimum currents flowing through the LEDs were adjusted while the output of the amplifier was monitored to assure that distinguishable and stable PPGs were observed from each PD pair and the electronics were not saturated.

Two sets of measurements were acquired. In the first set of experiments we kept the currents supplied to the LEDs at a constant level and compared the magnitude of the PPGs from each pair of PDs. To estimate the minimum current required to drive the LEDs in each configuration mode, we performed another series of measurement where the driving currents were adjusted until the amplitude of each PPG reached approximately a constant magnitude.

RESULTS

The amplitudes of the PPG signals measured by each pair of PDs positioned in transmission, transflection and reflection modes while the LED driving currents were kept at a constant level are plotted respectively in Fig. 4. To compare each PPG signal, we also plotted in Fig. 5 the relative magnitudes of the corresponding AC components for the three configuration modes that were tested in this study. Analysis of the data clearly revealed that there is a considerable improvement in signal-to-noise ratio (SNR) in reflection mode compared to either transmission or transflection modes. Fig. 6 compares the relative driving...
Minimizing the current required to drive the LEDs is a critical design consideration in optimizing the overall power consumption of a wearable pulse oximeter. However, reduced LED driving currents has a direct impact on the incident light intensity and, therefore, could lead to deterioration in the quality of the PPGs. Consequently, lower LED drive currents could result in unreliable and inaccurate reading by a pulse oximeter.

Designing a practical wearable pulse oximeter for long-term monitoring presents several unique challenges. In addition to user acceptability, the other most important issues to consider are sensor attachment and power consumption. For example, utilizing disposable tape or a reusable spring-loaded device for attachment of a pulse oximeter sensor to the fingertip, as commonly practiced in clinical medicine, poses significant limitations in prolonged monitoring applications. Therefore, the elaborate ring-shaped pulse oximeter sensor suggested by Rhee et al [8] offers an attractive alternative. Furthermore, as shown in Fig. 1, since the physical configuration of a ring-shaped device provides space for mounting several discrete PDs in three distinct orientations relative to the position of the LEDs, it is important to investigate which configuration would be more desirable in terms of overall power efficiency.

From the data presented in Figs. 4 and 5, it can be observed that the amplitude of the AC components depends on the location of the PDs inside the ring. Keeping a constant LED drive current and the same active area for each PD pair to facilitate easy comparisons, we found that the RMS magnitude of the PPGs was the highest in reflection mode and their values decreased considerably when measurements were obtained from the PDs positioned in transflection or transmission modes.

The data plotted in Fig. 6 show that in order to produce the same PPG amplitudes, increasingly more current is required if measurements are performed in transmission compared to reflection or transflection modes. In comparing the three different detection modalities, we found that transflection and transmission modes consume approximately 4-6 times more current compared to reflection mode. This result is expected since higher incident light intensities must be produced in order to overcome the larger optical attenuation encountered in transmission compared to transflection or reflection modes.

The current consumed by the LEDs in a battery operated portable wearable pulse oximeter is inversely proportional to the battery life. Therefore, we used the driving currents plotted in Fig. 6 to estimate the expected battery life of a typical 220mAh Lithium type coin 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 operating modes tested in this study assuming that the LEDs are pulsed continuously at a typical duty cycle of approximately 1.5%.

<table>
<thead>
<tr>
<th>Sensor Modes</th>
<th>Estimated Battery Life (Days)</th>
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<tbody>
<tr>
<td>Reflection</td>
<td>19</td>
</tr>
<tr>
<td>Transflection</td>
<td>6</td>
</tr>
<tr>
<td>Transmission</td>
<td>3</td>
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Note that the estimated values given in Table 1 are very conservative since they rely only on the power consumption by the LEDs and do not take into account additional power demands imposed by other components of a pulse oximeter. Nevertheless, the considerable differences in the estimated power consumptions clearly points out the practical advantage gained by using a
reflection rather than transflection or transmission modes in extending the battery longevity.

CONCLUSION

Minimizing the current required to drive the LEDs is a critical design consideration in optimizing the overall power consumption of a wearable pulse oximeter. In this study we investigated the potential power saving in a ring-shaped sensor configuration comprising multiple photodetector elements that were positioned in transmission, transflection and reflection modes. Preliminary in vivo experiments revealed that battery longevity could be extended considerably by employing reflection rather than transflection or transmission based measurements.

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