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ScienceDirect

ICT Express 2 (2016) 195–198

www.elsevier.com/locate/icte

Reflectance pulse oximetry: Practical issues and limitations☆

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Received 14 August 2016; received in revised form 10 October 2016; accepted 11 October 2016
Available online 9 November 2016

Abstract

The demand for reflective-mode pulse oximetry to monitor oxygen saturation has been continuously increasing because it can be used at diverse measurement sites such as the feet, forehead, chest, and wrists. For the wrists, in particular, pulse oximeters are easily available in the form of a band or watch. In this study, we developed a reflectance pulse oximeter and used it to measure oxygen saturation levels at the fingertips and the wrist. We analyzed the performance of this oximeter to address the challenges and limitations associated with using reflective-mode oximeters at the wrist for clinical purposes.

Keywords: Pulse oximetry; Reflective mode; Wrist; Wearable sensor

1. Introduction

Pulse oximetry is a noninvasive method for accurately estimating oxygen saturation (SaO_2) by reading the peripheral oxygen saturation (SpO_2). As SaO_2 and SpO_2 are sufficiently correlated and pulse oximetry has the advantages of being safe, convenient, inexpensive, and noninvasive, this approach is clinically accepted for monitoring oxygen saturation [1,2].

Pulse oximetry is simple to carry out; it only uses two different light sources and a photodiode [3–5]. Depending on the measurement site, either the transmissive or the reflective mode can be used. In the transmissive mode, the light sources and photodiode are opposite to each other with the measurement site between them. Light then passes through the site. In the reflective mode, the light sources and photodiode are on the same side, and light is reflected to the photodiode across the measurement site.

Currently, the transmissive mode is the most commonly used method because of its high accuracy and stability. Nevertheless, the demand for reflective-mode oximetry is continuously increasing because it does not require a thin measurement site. It can be used at diverse measurement sites such as the feet, forehead, chest, and wrists. In particular, if the wrist is the available measurement site, pulse oximeters can be conveniently used in the form of a band or watch. To the best of our knowledge, reflectance pulse oximetry, specifically for monitoring oxygen saturation at the wrist, is currently not practiced clinically. In recent years, many reflectance pulse oximeters have become commercially available, but they are only for personal monitoring of oxygen saturation and for entertainment purposes. Obviously, the focus is on developing oximeters for medical purposes, and research is being carried out in this regard. Furthermore, most research papers discuss only the basic principle of pulse oximetry and its utilization in smart devices; only a few papers discuss the challenges associated with reflective pulse oximetry.

In this study, we developed a reflectance pulse oximeter and addressed the practical issues and limitations associated with its use. Using this oximeter, we investigated the results of AC amplitudes and DC offsets of the red and infrared signals, including modulation ratio, which are critical factors to estimate SpO_2. We first tested our device by measuring oxygen saturation at a fingertip and wrist and analyzed its performance. Finally, we summarized all issues and discussed the feasibility of using the device for clinical purposes.

2. Methods

2.1. *Principle of* SpO_2 *estimation*

Pulse oximetry measures arterial oxygen saturation based on the light absorption properties of blood. When it combines with

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Peer review under responsibility of The Korean Institute of Communications Information Sciences.

☆ This paper is part of a special issue titled Special Issue on Emerging Technologies for Medical Diagnostics guest edited by Ki H. Chon, Sangho Ha, Jinseok Lee, Yunyoung Nam, Jo Woon Chong and Marco DiRienzo.

http://dx.doi.org/10.1016/j.icte.2016.10.004

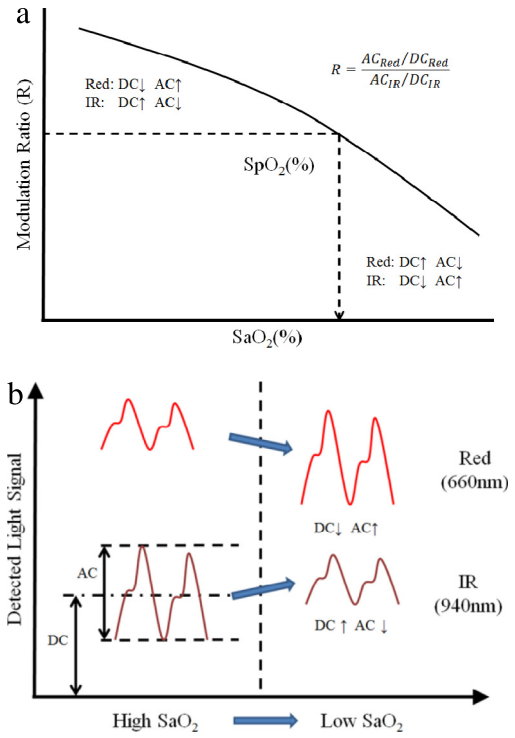

Fig. 1. (a) Changes in AC_R, AC_{IR}, DC_R, and DC_{IR} with decreased SaO_2. (b) Empirical relationship between modulation ratio R and SaO_2.

oxygen, deoxyhemoglobin (Hb) changes its light absorption characteristics. Pulse oximetry exploits the light absorption difference between Hb and oxygenated hemoglobin (HbO_2). HbO_2 absorbs more infrared light (660 nm wavelength) and lesser red light (940 nm wavelength) than Hb. In the transmissive mode, light from a pair of red and infrared light-emitting diodes (LEDs) is transmitted through a fingertip. Then, the transmitted light is received by a photodiode on the opposite side. The transmitted light signals consist of a direct current (DC) component and pulsatile alternating current (AC) component. Pulse oximetry calculates the modulation ratio R by using the DC and AC components of the red and infrared signals as follows:

$$R = \frac{AC_R/DC_R}{AC_{IR}/DC_{IR}}, \tag{1}$$

where AC_R and AC_{IR} are the AC amplitudes of the red and infrared signals, respectively [6,7]. DC_R and DC_{IR} are the DC offsets of the red and infrared signals, respectively. Then, empirically derived calibration curves are used to estimate SaO_2 based on the modulation ratio R, as seen in Fig. 1(a). AC_R and DC_{IR} increase with decreasing SaO_2, as seen in Fig. 1(b). On the other hand, AC_{IR} and DC_R decrease.

2.2. Reflectance pulse oximeter

We developed a reflective pulse oximeter where the LED

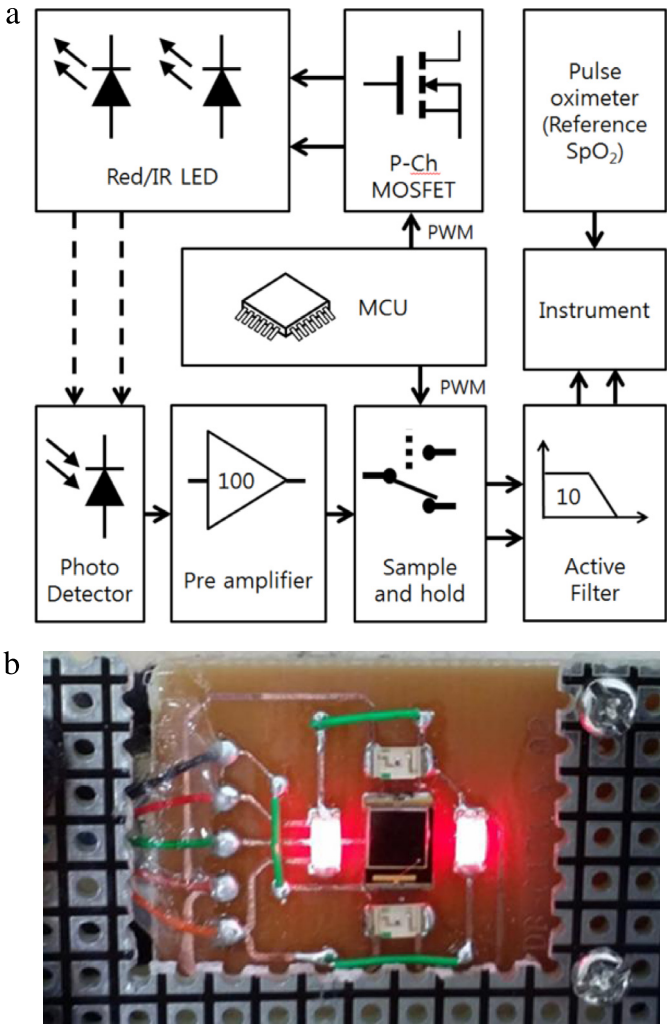

Fig. 2. (a) Control and data flow. (b) Developed reflectance pulse oximeter.

same side. To switch between red and infrared LED lights, the duty cycle was set to 50% with a switching frequency of 500 Hz, which generated a pulse width modulation signal through the microcontroller unit (MCU). Then, each reflected light beam was converted to an electrical signal, which was subsequently amplified with a gain of 100. A sample-and-hold circuit consisting of an analog switch and operational amplifier then separated each amplified signal with a sampling rate of 500 Hz from red and infrared LEDs. Each separated signal was then filtered using a low-pass filter with a cutoff frequency of 10 Hz and an additional gain of 10. For this study, we used an MCP6004 operational amplifier, a TM4C123GHPM MCU, an NJL5310R photodiode, an SML-LX0805SRC-TR red LED, and a KP-2012F3C infrared LED. Fig. 2 shows our design and its implementation in reflectance pulse oximetry. The maximum LED current was 20 mA, and the light intensity was set to the maximum level of the LED capability.

To determine AC_R, AC_{IR}, DC_R, and DC_{IR}, we first detected the pulse peak by incorporating a filter bank with variable cutoff

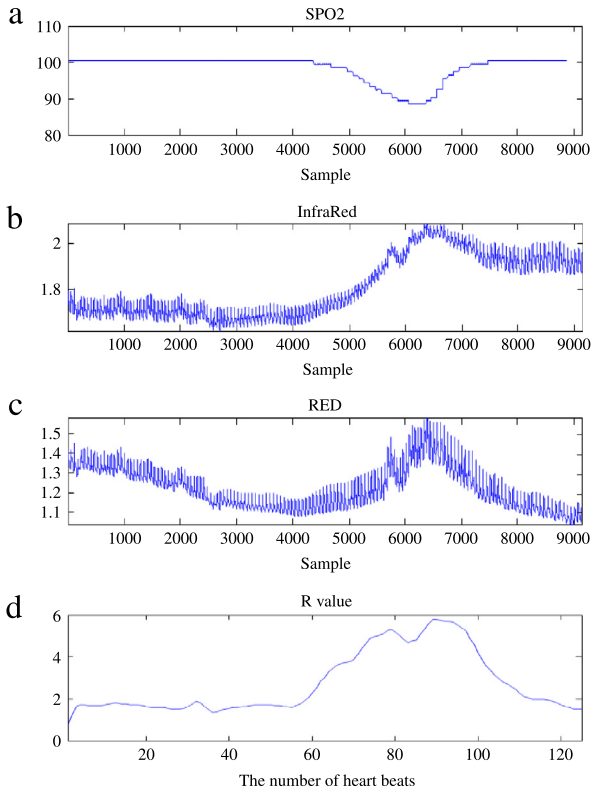

Fig. 3. Results for fingertip: (a) Reference SpO_2 (%), (b) reflected infrared raw signal, (c) reflected red raw signal, and (d) the modulation ratio R.

nonlinear filter, and decision logic [8]. Next, we calculated the average values of a 1-s segment signal with each detected peak as its center. Finally, DC was calculated from each average value, and AC was calculated by subtracting DC from each peak value. This method was applied to both red and infrared signals to determine AC_R, AC_{IR}, DC_R, and DC_{IR}.

2.3. Performance evaluation

We performed two experiments: one at a fingertip and the other at a wrist. In each experiment, the subjects breathed regularly for 40 s and then held their breath for as long as they could. Subsequently, an additional 1 min was given for their SpO_2 levels to return to the normal state. PowerLab 8/35 (ADINSTURMENTS, Sydney, Australia) was used with an oximeter pod (ADINSTRUMENTS, Sydney, Australia) to measure the reference SpO_2.

3. Results and discussion

3.1. Results for the fingertip

Fig. 3 shows the results for the fingertip: the reference SpO_2, reflected infrared raw signal, reflected red raw signal, and modulation ratio R. As expected, the ratio R increased with decreasing SaO_2. Fig. 4 shows the resultant AC_{IR}, AC_R,

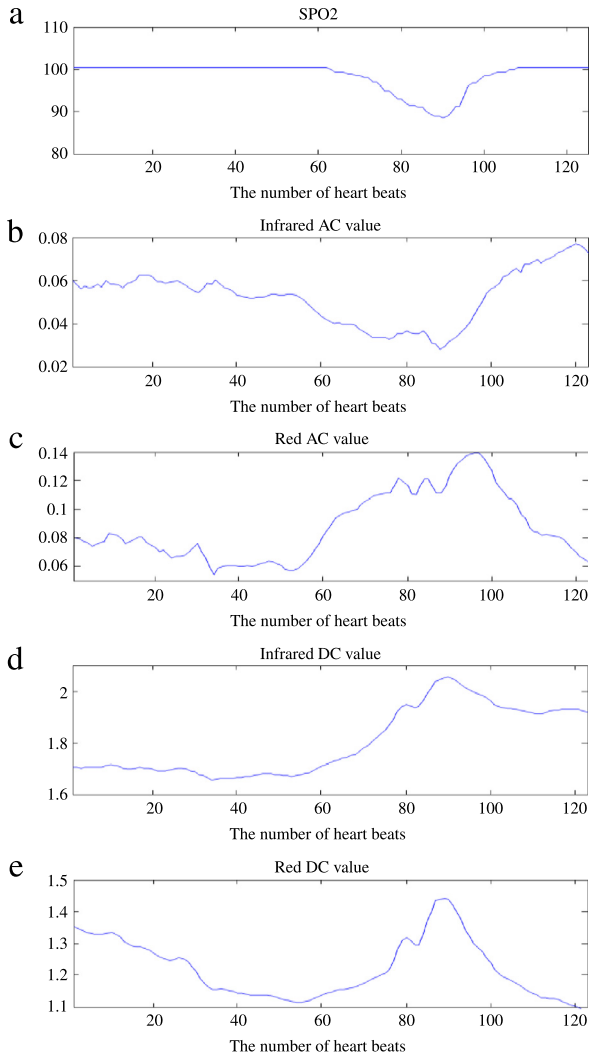

Fig. 4. Results from fingertip: (a) Reference SpO_2 (%) measured at fingertip, (b) resultant AC_{IR}, (c) resultant AC_R, (d) resultant DC_{IR}, and (e) resultant DC_R.

AC_R increased, which sufficiently match the light absorption characteristics described in Fig. 1(a) and (b). On the other hand, the reflected DC components partially reflected these characteristics. As SaO_2 decreases, DC_{IR} should increase and DC_R should decrease. However, in the results, only DC_{IR} followed this pattern. In fact, DC_R showed an increase. This behavior can be attributed to the fact that the reflective mode is more sensitive to pressure and ambient light sources, which leads to DC instability.

3.2. Results for the wrist

Fig. 5 shows the results for the wrist: the reference SpO_2, the modulation ratio R, AC_{IR}, AC_R, DC_{IR}, and DC_R. As SpO_2 decreased, the modulation ratio R increased as expected. However, the modulation ratio R was less stable than that for

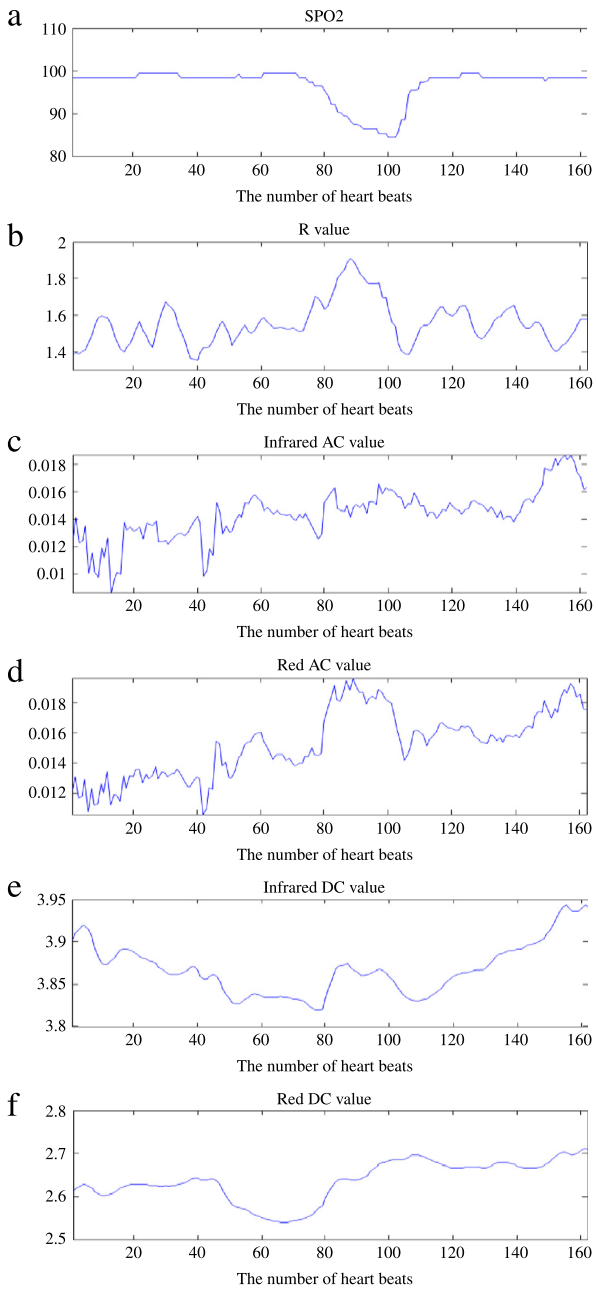

Fig. 5. Results for wrist: (a) Reference SpO_2, (b) modulation ratio R, (c) resultant AC_{IR}, (d) resultant AC_R, (e) resultant DC_{IR}, and (f) resultant DC_R.

not reflect the light absorption characteristics. Furthermore, the change in AC_R was less pronounced than that observed for the fingertip. Similarly, the reflected DC components did not reflect the characteristics well. This variation may be because the reflective mode has a low signal-to-noise ratio (SNR) and is sensitive to pressure and ambient light sources.

3.3. Discussion

Based on the performance of the oximeter, monitoring SpO_2 at the wrist using the reflective mode presents challenges with regard to clinical use. Another limitation is that the reflected red and infrared pulses can only be used for specific areas, such as a radial artery; thus, most areas of the wrist are not available for monitoring. In addition, a slight position change at the measurement site significantly affects the performance of the oximeter. Thus, the focus of research studies involving oximetry should be on choosing appropriate measurement sites, and optimizing pressure, ambient light, and SNR.

Acknowledgment

This study was supported by a Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning: NRF-2015M3A9D7067215.

References

[1] K.K. Tremper, Pulse oximetry, Chest J. 95 (4) (1989) 713–715.
[2] T. Aoyagi, Pulse oximetry: its invention, theory, and future, J. Anesth. 17 (4) (2003) 259–266.
[3] J.E. Sinex, Pulse oximetry: principles and limitations, Amer. J. Emerg. Med. 17 (1) (1999) 59–66.
[4] T. Aoyagi, M. Fuse, N. Kobayashi, K. Machida, K. Miyasaka, Multiwavelength pulse oximetry: theory for the future, Anesth. Analg. 105 (6) (2007) S53–S58.
[5] R. Ortega, C.J. Hansen, K. Elterman, A. Woo, Pulse oximetry, N. Engl. J. Med. 364 (16) (2011) e33.
[6] Y. Mendelson, Pulse oximetry: theory and applications for noninvasive monitoring, Clin. Chem. 38 (9) (1992) 1601–1607.
[7] T.L. Ferrell, P. Crilly, S. Smith, A.L. Wintenberg, C.L. Britton Jr, G.W. Morrison, M. Ericson, D. Hedden, D.W. Bouldin, A. Passian, Medical telesensors, in: BiOS'98 International Biomedical Optics Symposium, International Society for Optics and Photonics, 1998, pp. 193–198.
[8] M. Aboy, J. McNames, T. Thong, D. Tsunami, M.S. Ellenby, B. Goldstein, An automatic beat detection algorithm for pressure signals, IEEE Trans. Biomed. Eng. 52 (10) (2005) 1662–1670.