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Reflectance Forehead Pulse Oximetry: Effects of Contact Pressure During Walking

Russell P. Dresher*, Yitzhak Mendelson, *Member, IEEE*

Abstract—**Steady progress has been made towards the development of a reliable wearable pulse oximeter to aid first responders in remote monitoring and triage operations. This study was undertaken to assess how varying contact pressures affects the photoplethysmographic (PPG) signal, and arterial oxygen saturation (SpO_2) and heart rate (HR) measurement errors during motion artifact inducing activity. The study revealed that contact pressures ranging from 8 - 12 kPa resulted in the largest PPG amplitude for a reflectance sensor attached to the forehead region above the eye, although the signal-to-noise ratio (SNR) did not improve significantly. However, SpO_2 and HR errors increased when insufficient contact pressure was applied. This information may be helpful in the design of a more robust pulse oximeter sensor for use in remote monitoring applications.**

I. INTRODUCTION

The use of remote physiological status monitoring (RPSM) in determining an individual's health status has been gaining interest in recent years. Some military and civilian populations that could benefit from RPSM include soldiers, medics, firefighters, runners, and hikers [1]-[9]. A wireless physiological monitor in these situations could be used for applications ranging from remote triage during combat to early detection of possible health problems so treatment can be administered more expeditiously.

One potentially attractive approach for use in these situations is to use a wearable pulse oximeter to wirelessly transmit HR and SpO_2 information to a remote location. Having access to this vital information could aid in the assessment of injured persons operating in dangerous and stressful conditions.

Pulse oximetry relies on measurements of transmittance or reflectance photoplethysmographic (PPG) signals produced by variations in the quantity of arterial blood associated with periodic contractions and relaxations of the heart. Previous studies have shown that PPG signal amplitudes are affected by contact pressure applied on the pulse oximeter sensor [10]-[12]. These studies indicate that there may be a range of contact pressures that yield the greatest PPG amplitudes. Additionally, measurement error due to compromised blood circulation, a consequence of excessive contact pressures, or weak PPG signals resulting from insufficient contact pressure, may be reduced [13], [14]. Furthermore, contact pressures yielding the largest PPG amplitudes may result in the highest signal-to-noise ratios (SNR) leading to lower measurement errors during motion artifact inducing activity.

For pulse oximetry to become an effective means for RPSM, measurement errors due to motion artifacts must be minimized. We hypothesized that by securing the sensor to the skin with a contact pressure that results in the largest PPG amplitude, SNR will be improved and measurement errors due to motion artifacts will be reduced. The primary goal of this study was to determine a range of contact pressures yielding the largest PPG amplitudes for a reflectance sensor attached with an elastic band to the forehead region above the eye. Previous studies suggest that this location and attachment method may improve measurement accuracy [15]-[16]. A secondary goal of the study was to determine if the degree of SNR improvement resulting from increased PPG amplitudes is great enough to lower SpO_2 and HR errors in the presence of motion artifacts.

II. *IN VIVO* TESTING

Ten volunteers, 21-24 years old, took part in this study. Fig. 1 illustrates the experimental setup. A National Instruments RS-232 serial-to-USB hub was utilized for the simultaneous measurement of PPG, SpO_2, and HR data from two commercial Nonin^{TM} (Plymouth, MN) 8000R reflectance sensors. The output of the hub was connected to a laptop PC outfitted with a custom LabVIEW software program for simultaneous real-time data recording. A compressive load cell (MSI, Hampton, VA) was used to measure the force applied on the sensor. The LabVIEW program subsequently converted the force to pressure, according to the relationship

$$P = \frac{F}{A} \tag{1}$$

where, P denotes the pressure, F is the force, and A corresponds to the area of the sensor in contact with the skin.

A. Investigation of Contact Pressure and PPG Amplitude

The forehead sensor was mounted approximately 3 cm above the eyebrow. A similar fingertip sensor served as a

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*Corresponding author - R. P. Dresher obtained a M.S. degree in Biomedical Engineering at Worcester Polytechnic Institute, Worcester, MA 01609 USA. He is currently a Biomedical Engineering PhD candidate at Purdue University, West Lafayette, IN 47906 USA; Phone: 570-590-4000; e-mail: rdresher@verizon.net.

Y. Mendelson is a professor of Biomedical Engineering at Worcester Polytechnic Institute, Worcester, MA 01609 USA (email: ym@wpi.edu).

reference. Subjects rested in a comfortable prone position. To vary contact pressures, each subject was asked to push on the forehead sensor according to the pressure displayed by the PC and maintain a constant pressure while measurements were recorded. Pressures were changed from 4-40 kPa in approximately 2 kPa step increments. At each pressure level, data were collected for 20 s intervals.

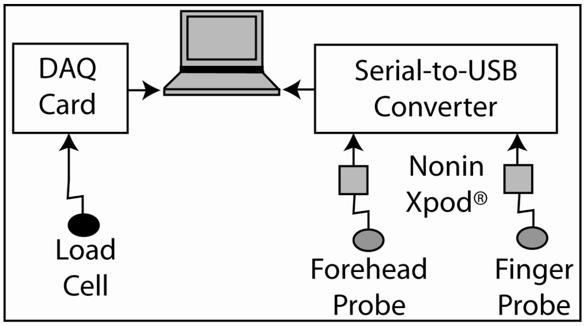

Figure 1. Experimental setup for PPG, SpO_2, and HR measurements.

For each pressure level, the mean amplitude of the PPG, mean SNR, and mean absolute SpO_2 and HR errors between the forehead and fingertip sensors were calculated by a dedicated MATLAB® program. SNR was defined as

$$SNR = \frac{A_{signal}}{A_{noise}} \tag{2}$$

where, A_{signal} was taken to be the area under the power spectrum from 0.1 Hz to the 3rd harmonic of the HR frequency and A_{noise} was taken to be the area under the curve for frequencies greater than the 3rd harmonic. Errors were defined as the difference between forehead and fingertip measurements.

B. Effects of Contact Pressure on Errors During Motion

The forehead sensor was fitted snugly inside a custom housing, depicted in Fig. 2, and secured to the forehead with an elastic headband. Three independent trials were conducted. In each trial, the sensor was secured with a different contact pressure. The contact pressure was measured by the load cell before the onset of motion. The contact pressures investigated were chosen based on the results of Part A, such that the effects of low pressure and PPG amplitudes (4 kPa), largest PPG amplitudes (12 kPa), and high pressures yielding lower PPG amplitudes (27 kPa) could be compared.

During this study, subjects were asked to rest their hand with the fingertip mounted sensor on the treadmill's support rail so that reference PPG signals free of motion-induced artifacts could be obtained. The treadmill's speed was set to a moderate-walking pace of 1.8 m/s and subjects were asked to maintain this pace for 2 minutes while the data were recorded.

After data were acquired, the reference PPG signal was inspected and if significant instances of motion artifacts were observed, they were deleted from both data sets. A dedicated MATLAB® program calculated the mean absolute SpO_2 and HR errors and detected SpO_2 and HR measurement dropouts. Dropouts were defined as SpO_2 measurements equal to 0 % or greater than 100 % and HR measurements equal to 0 bpm or 255 bpm.

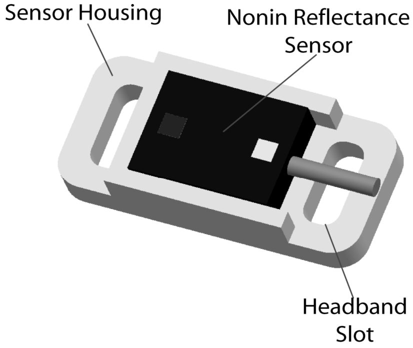

Figure 2. Custom sensor housing for sensor attachment to the forehead.

III. Results

Fig. 3 illustrates the effects of variations in contact pressure on the PPG signal amplitudes. For consistency among subjects, PPG signals were normalized to the largest observed amplitude for each individual. Accordingly, each data point on the graph represents the mean normalized amplitude for all 10 subjects. As clearly noticeable, contact pressures ranging between 8-12 kPa resulted in the statistically largest PPG amplitudes.

Fig. 4 shows the effects of varying degrees of contact pressures on SpO_2 and HR errors while subjects remained motionless for equally spaced contact pressure intervals. Mean measurement errors did not exceed the specified accuracy of the Nonin™ Xpod pulse oximeter (i.e., ± 2 digits for SpO_2 and ± 3 digits for HR readings).

Changes in SNR with increasing contact pressures are summarized in Fig. 5. In both cases (Fig. 4 and 5), Kruskal-Wallis one-way ANOVA on ranks concluded that measurement errors or SNR were not significantly affected by the contact pressures studied ($p>0.05$).

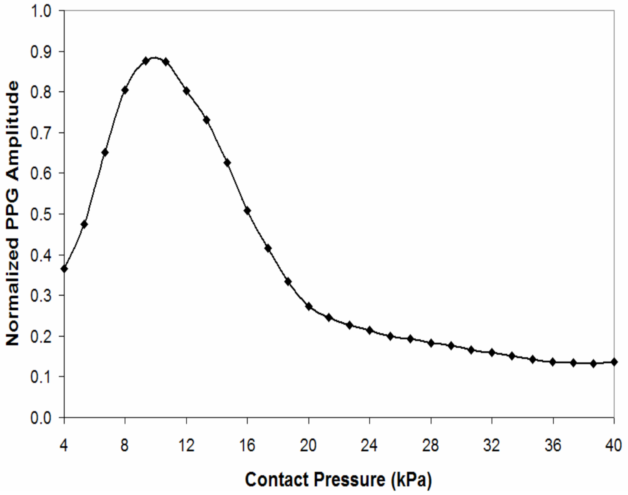

Figure 3. Effects of contact pressure on normalized PPG amplitudes.

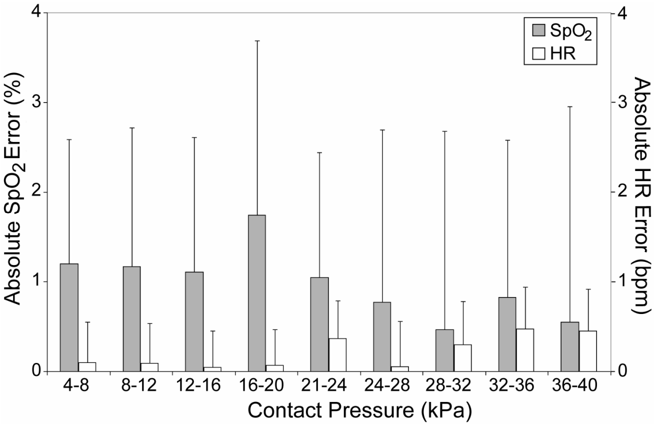

Figure 4. Effects of contact pressure on SpO_2 and HR errors during rest. Vertical line represents +1 SD.

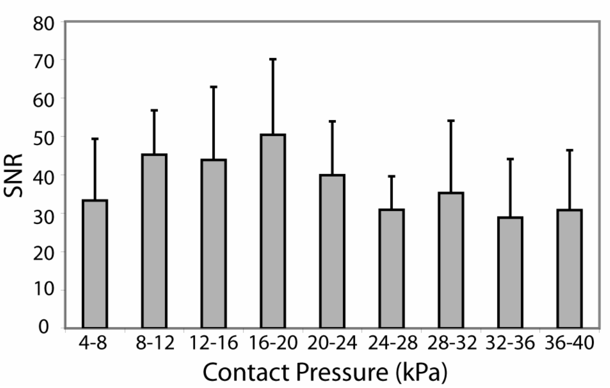

Figure 5. Effects of contact pressure on SNR during rest. Vertical line represents + 1 SD.

The effects of contact pressure on SpO_2 and HR errors from 3 different contact pressures equal to 4 kPa, 12 kPa, and 27 kPa during walking are shown in Fig. 6. These errors do not include instances of measurement dropouts. Kruskal-Wallis one-way ANOVA on ranks concluded that there was a statistically significant difference in SpO_2 measurement error for a contact pressure of 4 kPa, indicating that measurement errors are reduced when a contact pressure of 4 kPa was applied ($p<0.05$). Although no significant difference existed, a contact pressure of 4 kPa resulted in the largest mean HR error.

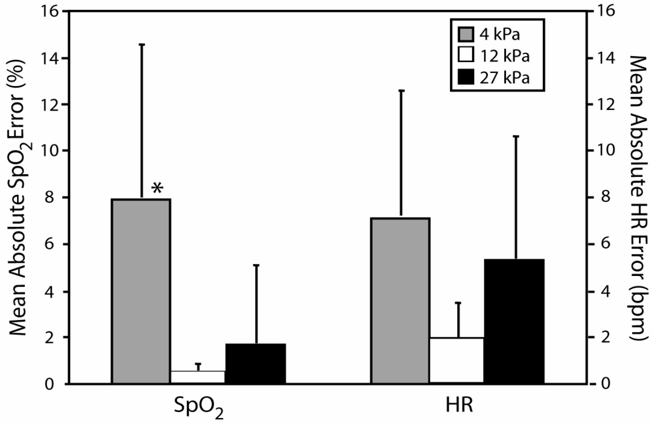

Figure 6. Effects of contact pressure on SpO_2 and HR errors during walking. Vertical line represents +1 SD. * indicates significant difference.

Fig. 7 illustrates the effects of varying contact pressure on the frequency of SpO_2 and HR measurement dropouts during walking. Kruskal-Wallis one-way ANOVA on ranks concluded that there was a statistically significant difference in the percentage of SpO_2 and HR dropouts for a contact pressure 4 kPa. This indicates that measurement reliability is improved when the sensor was better secured using higher pressures ($p<0.05$).

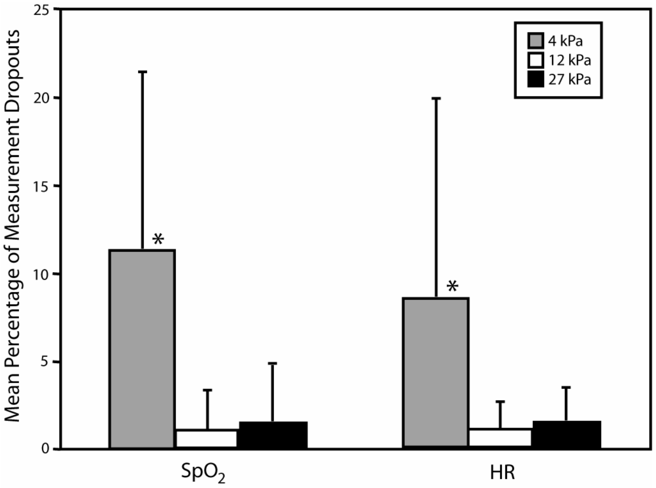

Figure 7. Effects of contact pressure on SpO_2 and HR measurement reliability during walking. Vertical line represents +1 SD. * indicates significant difference.

IV. DISCUSSION

The changes in PPG amplitudes with increasing contact pressure shown in Fig. 3 follow a similar trend observed in previous studies [10], [12]. The decrease in PPG amplitude around 12 kPa (90 mmHg) was expected due to occlusion of arterial blood flow underneath the sensor. However, despite local arterial occlusion, it was evident that the PPG signal did not completely vanish even at significantly higher contact pressures around 40 kPa (300 mmHg). We believe that the reason we could record discernable PPG signals at that higher pressure level is due to the ability of the light from the sensor LEDs to spread laterally beyond the occluded vascular bed where it can interact with pulsatile arterial blood in the vicinity of the sensor.

Based upon the SpO_2 and HR errors presented in Fig. 4, we could not conclude that measurement errors were significantly affected by contact pressure since all errors were below the specified accuracy of the Nonin^{TM} pulse oximeter. Furthermore, because errors remained relatively constant and within the specified accuracy of the device, the results obtained validate that contact pressures between 4 kPa and 40 kPa would be adequate to produce accurate SpO_2 and HR measurements.

The relatively constant values of SNR with increasing contact pressure illustrated in Fig. 5 further validate that contact pressures ranging between 4-40 kPa do not degrade the quality of the PPG signals. The data also suggests that the changes in PPG amplitude shown in Fig. 5 are not great enough to significantly affect the SNR and, therefore, any contact pressure between 4-40 kPa could be utilized for sensor attachment. Of course, for long term monitoring, a lower contact pressure would be preferred to avoid possible tissue damage due to prolonged ischemia.

Fig. 6 shows that mean SpO_2 and HR errors during walking are greater compared to contact pressures of 12 kPa or 27 kPa when securing the sensor with a contact pressure of 4 kPa. Also, as shown in Fig. 7, measurement dropouts occur most frequently for a contact pressure of 4 kPa. We believe that the resulting increase in measurement errors are due to movement of the sensor which would be more prevalent when a lower contact pressure is applied for securing the sensor to the forehead.

V. CONCLUSION

This study showed that securing a pulse oximeter sensor to the forehead region centered above the eye with pressures ranging from 8-12 kPa results in the greatest PPG amplitudes. However, we found that the gain in PPG amplitude in this pressure range did not improve SNR or reduced measurement errors. Attachment of a pulse oximeter sensor with contact pressures of 12 kPa and 27 kPa resulted in decreased SpO_2 and HR errors and improved measurement accuracy during walking compared to a contact pressure of 4 kPa because of insufficient contact pressure for sensor attachment to the forehead. Therefore, when securing a reflectance pulse oximeter sensor, a low contact pressure of about 4 kPa should be avoided but larger pressures can be used without a significant increase in measurement errors. However, additional studies should be conducted to investigate other types of motion artifact induced activities besides walking to confirm the above findings.

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REFERENCES

[1] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, “CodeBlue: An Ad Hoc Sensor Network Infrastructure for Emergency Medical Care,” *International Workshop on Wearable and Implantable Body Sensor Networks*, Apr. 2004.

[2] K. E. Friedl and J. H. Allan, “USARIEM: Physiological Research for the Warfighter,” *Army Medical Dept. Journal*, 4Q, 2004.

[3] U. Anliker, et al., “AMON: A Wearable Multiparameter Medical Monitoring and Alert System,” *IEEE Transactions. on Information Technology in Biomedicine*, 8(4), 2004.

[4] G. Ling, K. Day, P. Rhee, and J. M. Eckl und, “In Search of Technological Solutions to Battlefield Management of Combat Casualties,” *Proceedings of the SPIE Conference on Battlefield Biomedical Technology*, 3712, pp. 1-8, July 1999.

[5] Y. Mendelson, W. S. Johnston, and R. P. Dresher, “Forehead Measurements of Heart Rate and Heart Rate Variability from a Photoplethysmographic Reflectance Sensor: Effect of Motion Artifacts,” *Proceedings of the 3rd European Medical & Biological Engineering Conference*, Prague, Czech Republic, Nov. 2005.

[6] Y. Mendelson, R. P. Dresher, and A. Nagre, “The Feasibility of Measuring SpO_2 from the Head Using a Reflectance Pulse Oximeter: Effect of Motion Artifacts,” *Proceedings of the 3rd European Medical & Biological Engineering Conference*, Prague, Czech Republic, Nov. 2005.

[7] R. Kremens, J. Faulring, and D. Phillips, “A Compact Device to Monitor and Report Firefighter Health, Location, and Status,” *8th International Wildland Fire Safety Summit*, Missoula, MT, Apr. 2005.

[8] P. B. Crilly, E. T. Arakawa, D. L. Hedden, and T. L. Ferrell, “An Integrated Pulse Oximeter System for Telemedicine Applications,” *Proceedings of the IEEE Instrumentation and Measurements Conference*, Ottawa, Canada, May 1997.

[9] S. G, J. M. Wilson, A. Rathmell, and K. J. Riley, “Establishing Law and Order After Conflict,” *RAND Corporation*, Santa Monica, CA, 2005.

[10] X. F. Teng and Y. T. Zhang, “The Effect of Contacting Force on Photoplethysmographic Signals,” *Physiological Measurement*, 25, pp. 1323-35, 2004.

[11] R. P. Dresher and Y. Mendelson, “Attachment of a Wearable Skin Reflectance Pulse Oximeter,” *Proceedings of the 2005 BMES. Fall Meeting*, Baltimore, MD, Oct. 2005.

[12] C. Dassel, et al., “Reflectance Pulse Oximetry at the Forehead Improves by Pressure on the Probe,” *Journal of Clinical Monitoring*, 11(4), pp. 237-44, 1995.

[13] S. Rhee, B. H. Yang, and H. H. Asada, “Design and Evaluation of Artifact-Resistant Finger-Ring Plethysmographic Sensors,” *Proceedings of the ASME International Mechanical Engineering Congress & Exposition*, Orlando, FL, Nov. 2000.

[14] K. Shelley, et al., “The Effect of Venous Pulsation on Forehead Pulse Oximeter Wave Form as a Possible Source of Error in SpO_2 Calculation,” *Anesthesia & Analgesia*, 100, pp. 743-7, 2005.

[15] R. P. Dresher and Y. Mendelson, “Comparison of Suitable Attachment Techniques for a Wearable Forehead Reflectance Pulse Oximeter Designed for Remote Physiological Monitoring,” *Proceedings of the 1st Annual Medi Conference*, Hartford, CT, October 2005.

[16] P. D. Mannheimer, E. Konecy, and M. P. O’Neil, “The Influence of Larger Subcutaneous Blood Vessels on Pulse Oximetry,” *Journal of Clinical. Monitoring*, 18, pp. 179-88, 2004.