THE FEASIBILITY OF MEASURING SpO₂ FROM THE HEAD USING A REFLECTANCE PULSE OXIMETER: EFFECT OF MOTION ARTIFACTS

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Abstract: Although steady progress has been made towards the development of a more robust wearable pulse oximeter to aid in remote monitoring and triage operations by emergency first responders, the ability to extract accurate and reproducible information from a forehead pulse oximeter during extended periods of rigorous activity remains challenging. This preliminary field study was undertaken to assess whether SpO_2 measurements obtained from a commercial reflectance pulse oximeter sensor that was attached to several locations on the head using different attachment means can provide reproducible readings despite various degrees of motion artifacts. The study revealed that movement artifacts associated with various field activities can cause significant interruptions and lead to inaccurate measurements. However, despite this limitation, sufficiently accurate information might be obtained from a reflectance pulse oximeter sensor attached to the forehead by an elastic headband. This vital information may be helpful especially for emergency first responders during remote diagnosis and in life saving triage operations following a critical injury.

Introduction

The ability to detect life signs and perform triage remotely can potentially help to save many lives. For example, an awareness of the physiological status of soldiers on the battlefield, firefighters, hazardous material workers, or mountain climbers is important in improving risk management. Additionally, remote physiological monitoring can be important for support teams and emergency responders in making critical and often life saving decisions in order to expedite rescue operations [1–6].

One potentially attractive approach that can aid emergency medical teams in remote triage operations is the use of a wearable pulse oximeter to wirelessly transmit heart rate (HR) and arterial oxygen saturation (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 over large geographical terrains [7–8].

Although transmission pulse oximetry is widely utilized in clinical practice to measure HR and SpO_2 from a small probe that is normally attached to the fingertip, this method is not suitable for monitoring active persons in the field. Besides interfering with normal activities, for instance, hand movements can introduce significant motion artifacts, thereby leading to frequent measurement interruptions and erroneous readings.

Numerous clinical studies confirmed that transmission type pulse oximeters can produce unreliable information in the presence of motion artifacts [9−10]. Although manufacturers strive to improve the performance of their pulse oximeters by providing advanced signal processing algorithms that can minimize the effect of certain motion artifacts [11−12], to date, the extent to which pulse oximeters could provide reliable data in the field, where movement artifacts are more prevalent compared to clinical settings, remains largely unknown.

Forehead pulse oximetry has been used in clinical practice as an alternative approach to conventional transmission-based pulse oximetry when peripheral circulation to the extremities is compromised [13−14]. The feasibility of using a forehead reflectance pulse oximeter for automated remote triage was also suggested by Wendelken and co-workers [15], and several reports described the development of an improved wireless reflectance pulse oximeter that may be suitable for remote physiological monitoring [16–20]. However, limited studies investigated the suitability of a forehead pulse oximeter for field applications. Therefore, the primary objective of this study was to assess whether SpO_2 measurements obtained from a commercial reflectance pulse oximeter sensor that was attached to several locations on the head using different means can provide reproducible readings despite various degrees of motion artifacts.

Materials and Methods

Preliminary IRB-approved field studies were initially conducted using the data acquisition system described in Figure 1. The experimental setup consisted

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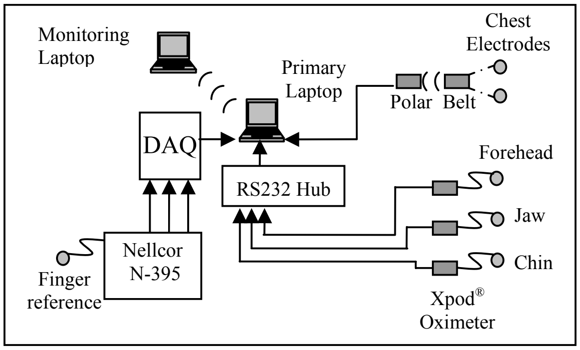

Figure 1: Data acquisition system for real-time monitoring during field testing [21].

of a Dell Inspiron™ 8500 laptop PC that was worn by a volunteer and was used as a primary computer for real-time data acquisition. The data acquired by the primary laptop PC were transmitted via a short-range wireless RF link and recorded by a second laptop PC that was used by the investigators to remotely track the data that were recorded from each subject.

Three Nonin Xpod® (Nonin Medical Inc., Plymouth, MN) pulse oximeters outfitted with reflection type sensors were used in a series of initial field tests to simultaneously record the subject's HR, SpO_2, and a photoplethysmogram (PPG). Pulse oximeter sensors were attached to the forehead, upper jaw, and chin using separate elastic bands. In addition, a Nellcor Model 395 transmission type pulse oximeter probe was mounted on the subject's finger using an adhesive wrap to record reference HR and SpO_2 readings. Reference HR readings were also recorded by a Polar S810i (Polar Inc., Lake Success, NY) heart rate monitor that was positioned across the subject's chest and interfaced to the recording PC via an infrared data link. Data were acquired in real-time using a LabVIEW™ program and custom software provided by the manufacturers.

A total of six healthy volunteers, 18-23 years old, participated in the initial study. Baseline recordings were initially acquired from each sensor while subjects were instructed to stand for about 2 minutes. Each volunteer was also instructed to rest on the ground either in a prone (face down) position, and on the left or right side. These positions were chosen to simulate possible scenarios associated with field injuries, and assess the effect of additional pressure that is exerted by the sensor on skin when an injury occurs and the injured subject may lie motionless on the ground. Following these initial baseline recordings, each person was guided through several short field exercises that consisted of walking, jogging, crawling, and jumping to introduce different degrees of motion artifacts. Each recording lasted approximately 2 minutes.

A second series of field studies were conducted by recording data from the forehead of two healthy volunteers, 23 years old, using three different sensor attachment techniques, as illustrated in Figure 2–4. One study (Fig. 2) was conducted after the sensor was secured to the skin by means of a medical adhesive Polyolefin™ tape (3M Medical Specialties, St. Paul, MN). A second set of data was recorded by sewing the sensor onto an elastic headband (Fig. 3). The third attachment method (Fig. 4) was based on sewing the sensor to the inner lining of a military helmet such that it was gently pressed against the forehead by the weight of the helmet.

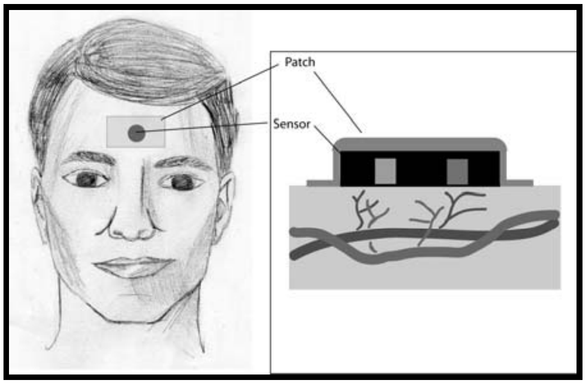

Figure 2: Illustrated view of the medical adhesive based sensor attachment.

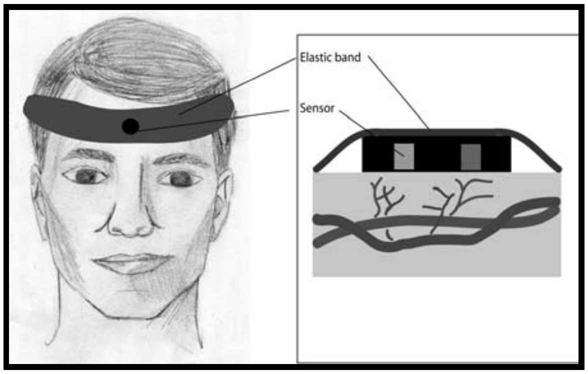

Figure 3: Illustrated view of the elastic headband attachment.

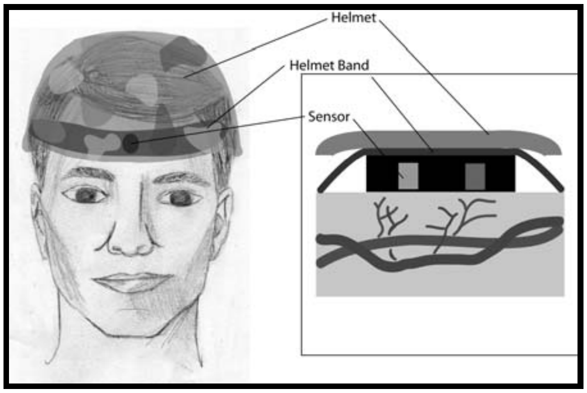

Figure 4: Illustrated view of the helmet-based sensor attachment.

Following two minutes of baseline recordings, each person was led through two minutes of short exercises that were intended to induce varying degrees of motion artifacts. These exercises consisted of slow paced walking (average speed 6 km/hr), running (average speed 13 km/hr), and jumping.

Results

Results from the initial series of field studies are summarized in Table 1. Each value represents the percentage of data points corresponding to SpO_2 readings ranging between 95%–100%. This range is generally considered to represent normal SpO_2 values for healthy subjects breathing ambient air.

Table 1: Percentage of SpO_2 readings between 95%–100% recorded from various facial locations during resting and short exercises.

Resting			
Orientation	Jaw	Chin	Forehead
Prone	92%	84%	99%
Left side	87%	92%	95%
Right side	94%	93%	98%
Standing	99%	89%	96%
Exercises			
Walking	83%	80%	73%
Jogging	77%	75%	79%
Jumping	89%	91%	97%
Crawling	65%	76%	84%

Figures 5–7 show typical effects caused by various degrees of motion artifacts recorded from the forehead during the second series of experiments. As indicated, walking induced sporadic motion artifacts that caused distortions of the PPG but we noticed that SpO_2 readings remained unperturbed. Running, on the other hand, produced more pronounced motion artifacts depending on the method used to secure the sensor to the forehead. Although some SpO_2 readings remained stable during running, we found that motion artifacts caused more significant distortions of the PPG. These artifacts were frequently accompanied by SpO_2 dropouts and resulted in inaccurate or missed readings. Also, results from this study showed that jumping induced the most significant amount of motion artifacts clearly causing a more frequent loss of the PPG signal and more prolonged periods of SpO_2 dropouts.

The data presented in Figure 8 and Table 2 provide another indication that motion artifacts associated with walking, jumping, or running can lead to significant errors. Among the three different attachment techniques tested in this study, we found that utilizing an elastic headband for securing the sensor to the skin produced the most accurate results. However, as the level of physical activity increased, we noticed a sharp drop in the ability to sustain reproducible readings.

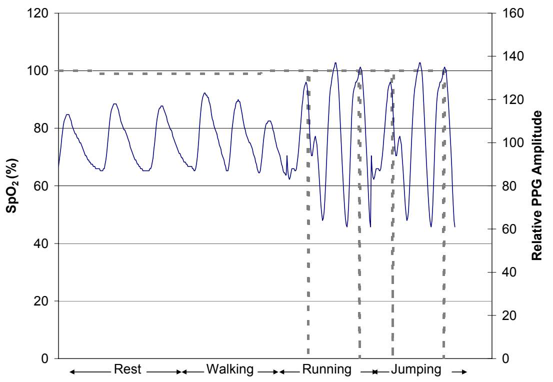

Figure 5: Effect of motion artifacts on PPG waveform and SpO_2 recordings from the forehead using an elastic headband attachment.

Figure 6: Effect of motion artifacts on PPG waveform and SpO_2 recordings from the forehead using the helmet to secure the sensor.

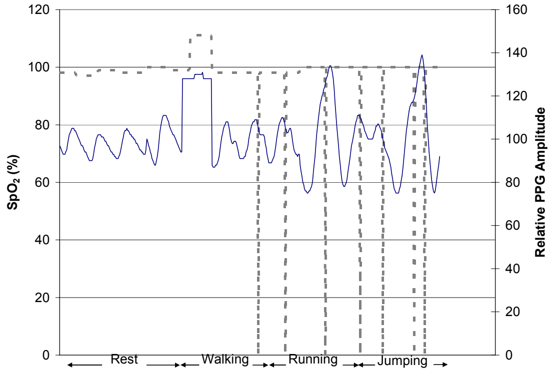

Figure 7: Effect of motion artifacts on PPG waveform and SpO_2 recordings from the forehead using adhesive attachment.

Discussion

Although steady progress has been made recently towards the development of a more robust wearable pulse oximeter to aid in remote monitoring and triage operations by emergency first responders, the ability to

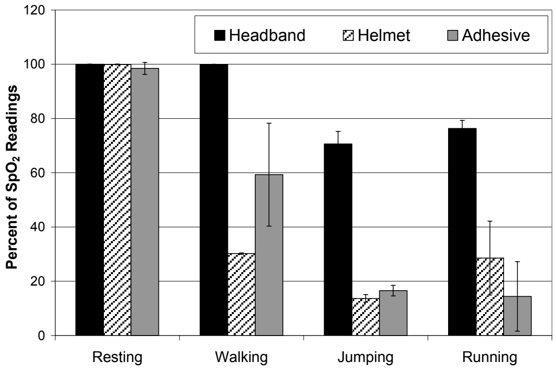

Figure 8: Percentage (± SD) of SpO_2 readings between 95-100% recorded from the forehead for different activities and sensor attachments.

Table 2: Percentages (± SD) of SpO_2 readings between 95%-100% measured from the forehead for different activities and sensor attachments.

	Resting	Walking	Running	Jumping
Headband	100 ± 0	100 ± 0	76.3 ± 2.9	70.6 ± 4.6
Helmet	99.9 ± 0.2	30.2 ± 0.3	28.6 ± 13.6	13.7 ± 1.4
Adhesive	98.5 ± 2.2	59.3 ± 19.0	14.4 ± 12.8	16.6 ± 2.0

extract accurate and reproducible information from a forehead pulse oximeter during extended periods of rigorous activity remains a technical challenge. This preliminary field study was undertaken to evaluate several potential attachment techniques and assess the effect of motion artifacts on readings recorded by a forehead pulse oximeter from different facial locations.

The results from the first series of experiments, as summarized in Table 1, indicate that even slow to moderate activities associated with walking or crawling can significantly affected the ability to obtain consistent readings irrespective of sensor location on the head. Analysis of the data revealed that, regardless of the specific activity involved, only about 78.5, 80.5, and 83.2 percent of the SpO_2 readings recorded from the jaw, chin, and forehead, respectively, corresponded to SpO_2 values ranging between 95–100%. Similarly, the data acquired during the second series of experiments (presented in Table 2) revealed that motion artifacts can cause significant errors, although the results suggest that a large portion of these errors can be eliminated by properly securing the sensor to the headband before it is mounted on the head.

While the majority of the interferences observed during this study were most likely caused by variations in the optical coupling between the sensor and the skin, as well as local perturbations in blood circulation associated with body movement, we believe that the relative movements of the three elastic headbands that were used to secure each sensor on the head during the first series of measurements may have inadvertently contributed to some of these errors.

This study suggests that the forehead could provide a convenient and more stable location for attaching a pulse oximeter sensor on a mobile person. However, it is important to keep in mind that the inaccuracies observed are troublesome if accurate and reproducible readings are expected while a person remains active. Although the Nonin Xpod® pulse oximeters used in this study are convenient to wear in the field, it should be noted that these units are primarily intended for spot checking applications and not for more rigorous field applications. Further studies are underway to evaluate more advanced “motion-resistant” pulse oximeters to determine if improved signal processing software can help to lower measurement inaccuracies when the subject remains active. Nevertheless, considering the likelihood that a person wearing a pulse oximeter in the field will quickly become immobile upon injury, it is reasonable to expect that SpO_2 readings from a forehead pulse oximeter will become sufficiently accurate for use by emergency first responders during remote diagnosis.

Conclusions

Although the forehead has been used in clinical settings as an alternative site for noninvasive monitoring of SpO_2 by a reflectance pulse oximeter, this study revealed that movement artifacts associated with various field activities could lead to inaccurate measurements. Despite this limitation, it should be possible to obtain sufficiently stable and accurate readings from an injured person wearing a properly secured small pulse oximeter sensor during high-risk missions. This vital information may be helpful especially for emergency first responders during remote diagnosis and in life saving triage operations following a critical injury.

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