Forehead Pulse Oximetry

Headband Use Helps Alleviate False Low Readings Likely Related to Venous Pulsation Artifact

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Background: This study investigated whether a tensioning headband that applies up to 20 mmHg pressure over a forehead pulse oximetry sensor could improve arterial hemoglobin oxygen saturation reading accuracy in presence of venous pooling and pulsations at the forehead site.

Methods: Healthy volunteers were studied breathing room air in supine and various levels of negative incline (Trendelenburg position) using the forehead sensor with the headband adjusted to its maximum and minimum recommended pressure limits. Saturation readings obtained from the forehead sensor with the subjects supine and the headband in place were used as a baseline to compare the effects of negative incline on reading accuracy when using and not using the headband. Occurrences of false low-saturation readings detected by forehead sensors were compared with those from digit sensors.

Results: No difference was observed between saturation readings obtained from the forehead sensor in supine and negative incline positions when the headband was applied. Forehead sensor readings obtained while subjects were inclined and the headband was not used were significantly lower (P < 0.05) than the supine readings. There was no statistically significant difference between the digit and forehead sensor in reporting false low-saturation readings when the headband was applied, regardless of body incline.

Conclusions: Application of up to 20 mmHg pressure on the forehead pulse oximetry sensor using an elastic tensioning headband significantly reduced reading errors and provided consistent performance when subjects were placed between supine and up to 15° head-down incline (Trendelenburg position).

PULSE oximetry, a standard noninvasive technique to monitor arterial hemoglobin oxygen saturation (SpO₂), is routinely used in the operating room, in the intensive care unit, and during emergency transport. There are two common types of pulse oximetry sensor configurations, referred to as transmission mode and reflectance mode. The transmission mode sensor is configured with the optical emitter and detector positioned on opposing surfaces of the tissue with sensors applied to, for example, a finger, ear lobe, or toe. In the reflectance mode sensor, the emitter and the detector are located side by side and the sensor can be applied to a single surface, such as on the forehead. With both sensor configurations, the emitter shines red and infrared light into the skin and the detector measures the scattered light that is transmitted through blood-perfused tissues.

Under normal conditions, arterial blood pulsation at the fingertip is more than adequate for the oximeter to use in determining the oxygen saturation. Hypothermia, hypotension, and peripheral vasoconstriction in digits, however, can greatly reduce the pulse size and lead to absent or erroneous SpO₂ readings.1–3 In these situations, the forehead provides an excellent alternative site to monitor SpO₂. Arteries that supply the forehead do not vasoconstrict in response to stimuli such as cold temperatures that otherwise affect the periphery.4–6 and can continue to provide adequate pulsations when the digits shut down.7 Furthermore, detection of hypoxia by the forehead site can occur 1–2 min sooner than the digit under such conditions of peripheral vasoconstriction.8,9 While the forehead may lend itself better to reflectance than transmittance sensor configurations, the vascular density of the region immediately above the eyebrow has been found to be sufficient to create the needed pulse size5 for reliable pulse oximetry using modern-day monitors.9 The other advantages of the forehead include less susceptibility to challenging motions as compared with the hands10 and easy accessibility to the sensor site in the operating room.

Although there are several advantages of monitoring SpO₂ with a forehead sensor, acceptance of the technology has been slow. One of the reasons for this relates to spuriously lower oxygen saturation readings that may be found under conditions (such as Trendelenburg positions or positive-pressure ventilation) that cause the venous blood in the local tissue to pulse synchronously with the right side of the heart.11–14 Applying a positive pressure to the sensor may improve reading accuracy by expelling this pooled and pulsing venous blood.11,15

Our objective was to test whether application of up to 20 mmHg pressure against the forehead reflectance sensor provides consistently accurate oxygen saturation readings.
readings in healthy volunteers in Trendelenburg position. We hypothesized that such pressure would reduce venous pulsations without compromising the arterial blood supply to the forehead needed for pulse oximetry. To achieve this, we developed a new headband that applies between 6 and 20 mmHg pressure at the sensor site. The headband has an elastic portion that covers the forehead and a tensioning indication region to guide in applying the headband to achieve the recommended pressure range (fig. 1). To test our hypothesis, we tested the system at each end of the tensioning zone that provides application of maximum (approximately 20 mmHg) and minimum (approximately 10 mmHg) levels of pressure on forehead sensor.

Materials and Methods

Pressure Variability Test

To verify that the pressure applied by the headband at the sensor did not exceed our target maximum of 20 mmHg with the headband adjusted to maximum tension, we asked eight clinicians to apply the headband (Oxi-Max MAX-FAST headband; Nellcor/Tyco Healthcare, Pleasanton CA; shown in fig. 1) on 10 healthy pediatric and adult volunteers with different head shapes (e.g., different head circumferences and hair types). The protocol was approved by the institutional review board (Independent Review Consulting, Inc., Corte Madera, CA) and informed consent was obtained from each subject before the study. A pressure transducer (Tact Array T-2000 pressure measurement system; Pressure Profile Systems, Los Angeles, CA) was used to measure pressure applied by the headband at the sensor site. The forehead pulse oximetry sensor (OxiMax MAX-FAST; Nellcor/Tyco Healthcare) was modified by replacing the optical portion with the pressure transducer.

Clinicians placed the modified sensor and the headband on study participants, as per the directions for use. Each clinician placed sensors on five volunteers. A total of 40 data points were collected. Pressures as measured with the transducer were automatically logged on a laptop computer.

Trendelenburg Position Study

After approval from the institutional review board, 11 healthy adult volunteers were studied using the forehead sensor with and without the headband and under two head-down Trendelenburg positions. The study was conducted over 2 days, first for minimal pressure application and then repeated for maximum pressure application.

While the true SpO2 necessarily ranges between 0% and 100%, the computation of SpO2 is subject to bias and noise in the measured optical signals and may result in values outside this span. Manufacturers typically display 100% when the calculated SpO2 value actually exceeds this. We used the monitor’s internally computed SpO2 value before its being truncated to avoid biasing our statistics that might otherwise result.

Fig. 1. The tensioning headband used in the study. Adjusting the tension (and the applied pressure over the reflectance sensor under the headband) is accomplished by pulling on the tensioning tab and attaching it to the base with a hook-and-loop fastener. The alignment arrow is adjusted to fall within the indicated tensioning range. The two images illustrate the headband adjusted for its lower (A) and higher (B) tension settings.

The same group of volunteers participated on both days. Participants breathed room air throughout the study.

Subjects were placed on a positional bed (Stryker Corporation, Kalamazoo, MI). The forehead sensor (OxiMax MAX-FAST) was applied directly above either the right or left eyebrow and slightly lateral to the center of the iris. Two digit sensors (OxiMax MAX-A; Nellcor/Tyco Healthcare) were applied to the right and left index fingers as reference sensors. Each sensor was attached to a pulse oximetry monitor (N-595, V 3.3.0.0; Nellcor/Tyco Healthcare), which in turn was connected to a computer for automatic continuous data logging at 1 Hz. The recorded SpO2 readings were allowed to exceed 100%. Data were collected from the forehead sensor with the headband applied at the minimum and maximum tension (pressure) indicators in supine position (0°) and with subjects rotated to −10° and −15° head-down incline positions (Trendelenburg position), first with the headband (HB1), then with the headband removed (W/OHB), and finally with the headband reapplied (HB2). Six data points, comprising the average of readings spanning 10 s, separated in time by 20 s, were collected for each observation. Subjects were returned to 0° for 1–2 min between the two inclined positions to eliminate transient venous pooling. No data were collected during this time. Each incline position was maintained for up to 20 min.

Statistical Analysis

The average of the six SpO2 observations at each test condition obtained by the forehead sensors at −10° and −15° Trendelenburg positions, HB1, W/OHB, and HB2 were compared with SpO2 readings at 0° HB1 using the paired t test and F test (the Kolmogorov-Smirnov test was used to verify that the data were consistent with a normal distribution). The occurrence of false low-satura-
tion (hypoxia) readings by the forehead and digit sensors at threshold values of 95%, 90%, and 85% \( \text{SpO}_2 \) during the various test conditions were compared using the chi-square test on the individual observation data (six per subject per condition to capture potentially transient false low readings). For each test, a probability value of \( P < 0.05 \) was considered significant.

Results

Pressure Variability Study

Ten volunteers, four male and six female, participated in the pressure variability study. The age range of the volunteers was between 5 and 55 yr. We observed that the maximum pressure applied by the headband varied between 10 and 17 mmHg (average 14.23 ± 1.73 mmHg). We confirmed that application of headband at the minimum tension indicator applied pressure between 6 and 12 mmHg in an independent benchtop test.

Trendelenburg Position Study

Eleven volunteers, two male and nine female, participated in the minimum pressure application study. The motion of two subjects caused displacement of the sensor at the \(-15^\circ\) Trendelenburg position incline during this part of the study; these data were not included in the final analysis. Ten volunteers, two male and eight female (one female subject did not return on the second day), participated in the maximum application pressure study. The age range of the volunteers participating in both studies was between 20 and 55 yr.

The sequence of the study and the effects of the body position and headband use can be seen in figure 2. Table 1 summarizes the observed \( \text{SpO}_2 \) readings under the studied conditions. We did not observe a statistically significant difference between the means or variances of \( \text{SpO}_2 \) readings at \( 0^\circ \) HB1 (control conditions) and readings at either incline during the initial headband placement. There was, however, a statistically significant difference compared with the control condition at both inclines when the headband was removed. Replacing the headband generally improved the performance but did not immediately restore the \( \text{SpO}_2 \) readings to the initial control values in most instances (\( P < 0.05 \)). Figures 3A and B pool all of the observed and average \( \text{SpO}_2 \) readings for the subjects at each headband condition.

Combining observations made during the two tensioning portions of the study and the two Trendelenburg positions, the total number of observed \( \text{SpO}_2 \) readings below 95%, 90%, and 85% obtained with the forehead sensor when no headband was used was greater than the with digit sensors (table 2). False low \( \text{SpO}_2 \) readings occurred in 62%, 33%, and 13% of the logged data with the forehead sensor at these three thresholds, respectively, compared with 10%, 0%, and 0% for the digit sensors (\( P < 0.001 \) at all three thresholds). Replacing the headband (HB2) greatly reduces

Table 1. Mean ± SD of Observed \( \text{SpO}_2 \) by Forehead Sensor at the Various Tested Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Low Tension</th>
<th>High Tension</th>
</tr>
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<tbody>
<tr>
<td>0° HB1</td>
<td>98.2 ± 2.0</td>
<td>98.6 ± 1.6</td>
</tr>
<tr>
<td>-10° HB1</td>
<td>97.3 ± 2.3</td>
<td>98.3 ± 1.4</td>
</tr>
<tr>
<td>-10° W/OHB</td>
<td>92.3 ± 7.2†</td>
<td>91.1 ± 6.2†</td>
</tr>
<tr>
<td>-10° HB2</td>
<td>97.1 ± 2.6</td>
<td>98.0 ± 1.9</td>
</tr>
<tr>
<td>-15° HB1</td>
<td>98.3 ± 2.0</td>
<td>98.1 ± 1.9</td>
</tr>
<tr>
<td>-15° W/OHB</td>
<td>94.5 ± 6.3†</td>
<td>89.5 ± 6.4†</td>
</tr>
<tr>
<td>-15° HB2</td>
<td>96.0 ± 4.9†</td>
<td>96.3 ± 2.7†</td>
</tr>
</tbody>
</table>

\( *P < 0.05 \) and \( †P < 0.01 \), compared with 0° HB1.

HB1 = headband applied before placing subject in a negative incline; HB2 = headband reapplied; \( \text{SpO}_2 = \) arterial hemoglobin oxygen saturation; W/OHB = without the headband.
the number of false low readings; however, they remained greater than the number of observations from the digit sensors at each of the thresholds ($P < 0.05$). There was no statistically significant difference in false low-Sp$_\text{O}_2$ readings between forehead and digit sensor usage at any of the thresholds when the headband was placed before tilting the subjects (HB1).

**Discussion**

Pulse oximetry detects arterial hemoglobin oxygen saturation by distinguishing the time varying “pulsatile” light absorbance of blood-perfused tissues to that of other non-pulsing tissues. The principle is based on the assumption that the detected pulsatile signal derives from only the arterial circulation; venous blood and other light absorbers in the surrounding tissue are nonpulsatile. Interference with the detected pulse signal can lead to erroneous Sp$_\text{O}_2$ readings. In digit sensors, the interference can occur as a result of excessive hand motion or excessive ambient light.$^{2,3}$ In addition, poor blood flow caused by conditions such as hypothermia, hypotension, or peripheral vasoconstriction can challenge the monitor’s ability to identify or isolate the pulsatile signal required for processing.$^{1,3}$ The forehead provides an alternative sensor placement site in such conditions because, unlike the digit, the forehead is
supplied by branches of the supraorbital artery (a branch of internal carotid artery) and is not susceptible to vasoconstriction.4,5

Some investigators have observed low SpO2 readings in the presence of normal co-oximetry values when using a forehead sensor and suggest venous pulsations as the most likely cause.14,15 The veins in the forehead that drain to the heart via the jugular vein lack valves. The jugular valve itself is incompetent in approximately 38% of adults.11 As a result, a continuous, pressurized column of blood can fill the veins under some circumstances (e.g., in Trendelenburg position), leading to venous engorgement in the forehead. Pulses generated from contraction of the right side of the heart reflect in the jugular vein as an a-c-v wave corresponding to right atrial contraction, bulging of the tricuspid valve in the right atrium, and ventricular systole, respectively. These cardiosynchronous jugular venous pulses may be transmitted to veins in the forehead in the presence of this continuous venous column. The pulse oximeter may not be able to distinguish these pulses from the normal arterial pulsation.14,15 The resulting SpO2 value becomes a mixture of the arterial and venous blood oxygen saturations.

Arteriovenous shunts17,18 and intracranial arterial pulsations11,19 may be other possible sources of forehead venous pulsations. Although not as prevalent as in fingers, toes, or palms, arteriovenous shunts are present throughout the skin, including the forehead, and enable the blood to bypass the capillaries. Similarly, intracranial arterial pulsations could be transmitted to the forehead veins via the superior ophthalmic vein. The superior ophthalmic vein receives tributaries from the superficial veins of the forehead via the angular vein and drains into the cavernous sinus. The cavernous sinus is located on either side of the sphenoid bone and posterior to the superior orbital fissure. The internal carotid artery passes on the medial wall of the cavernous sinus. Thus, the pulsations from the internal carotid artery could be directly transmitted through the cavernous sinus to the valve-free superficial ophthalmic vein and then to the superficial veins of the forehead.

We made our various Trendelenburg position forehead sensor reading comparisons to those of the forehead sensor when the subjects were at zero inclination, as opposed to comparing to the simultaneously available digit sensor SpO2 readings. As can be seen in figures 2 and 3, the digit sensor readings were not meaningfully affected by placing the subjects at a negative incline. Because of a small calibration difference in the two sensor types, however, digit readings did differ slightly from the forehead readings while the subjects were at normal oxygen saturation. Because the focus of this study was to evaluate the impact of the headband, we chose to assume the underlying SaO2 was stable for these subjects breathing room air, and compare instead the forehead SpO2 readings under the various test conditions with the forehead SpO2 readings under conditions absent of the perturbations (i.e., 0° HB1).

Approximately half of our subjects continued to display accurate SpO2 values when they were placed in Trendelenburg positions even when the headband was not used, i.e., the headband was not necessary in these subjects. This is consistent with the occurrence of competent jugular valves in most individuals as noted above. Readings with the remainder of the subjects, however, did become more reliable by using the headband.

Our goal in creating the new headband design was to apply a sensor application pressure that is lower than the average capillary pressure to maintain adequate blood supply in the region. Results of our study show that application of up to 20 mmHg external pressure improves the accuracy of SpO2 readings in the Trendelenburg position, most likely by increasing local tissue pressure, decreasing venous pooling, and therefore decreasing venous pulsations at the sensor site. We observed that when the headband was applied before placing subjects in the Trendelenburg position, the performance of the forehead sensor was consistent throughout the observation. When the headband was applied after the venous pooling was induced, accuracy of the SpO2 readings typically required several seconds to 5 min to recover (see fig. 2 when the headband was replaced during the second inclined position). Forehead SpO2 performance seems to be better when the headband is placed early than if it is placed after formation of venous pooling, although waiting for a few minutes will likely provide equivalent results.

Another interesting benefit of the applied pressure created by the headband can be seen in data presented in figures 2 and 3. We observed a greater number of SpO2 readings that exceeded “102%” (see footnote in the Materials and Methods section) in the lower headband ten-

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Table 2. Number of Observed Readings Below SpO2 Levels of 95%, 90%, and 85% Using Digit and Forehead Sensors, Combining the Collected Data at the Two Headband Tensions and Two Trendelenburg Position Angles

<table>
<thead>
<tr>
<th></th>
<th>&lt; 95% SpO2</th>
<th>&lt; 90% SpO2</th>
<th>&lt; 85% SpO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB1 Digit</td>
<td>19 (8%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W/OHB Digit</td>
<td>23 (10%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Forehead Digit</td>
<td>61* (25%)</td>
<td>11* (5%)</td>
<td>6* (3%)</td>
</tr>
<tr>
<td>Forehead W/OHB</td>
<td>34 (14%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HB2 Digit</td>
<td>148† (62%)</td>
<td>80† (33%)</td>
<td>32† (13%)</td>
</tr>
<tr>
<td>Forehead Digit</td>
<td>34 (14%)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Each of the values in the table is with respect to a total of 240 observations. * P<0.05 and †P< 0.001, compared with digit occurrence.

HB1 = headband applied before placing subject in a negative incline; HB2 = headband reapplied; SpO2 = arterial hemoglobin oxygen saturation; W/OHB = without the headband.
sion data set when the headband was removed than during the other periods (n = 16 of 186 observations W/OHB vs. 0 of 372 HB1 and HB2). Forehead sensor readings were more consistent in this respect when the headband was used at higher tension (n = 0 of 180 observations W/OHB). The high SpO2 values may have been caused, in part, by the sensors lifting slightly from the skin, creating an optical shunt that disrupted the pulse oximeter’s determination of relative red-to-infrared pulse size.20 When the headband was in place at either tension, the applied pressure on the back side of the sensor may have helped assure proper sensor contact with the skin. Use of the headband at the higher tension setting may also have helped set the sensor’s adhesive for maintaining this contact such that removal of the headband preserved the shunt-free environment, at least during our approximately 5-min monitoring period. Pul- sations in larger subcutaneous vessels may have also contributed to the high readings21; however, it is not clear why there would be a fewer number of observations when the headband setting was previously placed at the higher tension as opposed to the lower tension.

While we believe pulsing venous blood in local tissues to be the predominant source of the reading artifacts we observed when the headband was not used, our study protocol was not designed to specifically isolate the cause. Our efforts focused instead on evaluating the effectiveness of applying mild pressure to improve performance in an environment intended to create venous pulsation. Presuming that little else changes when tilting our subjects, potential causes of inaccurate readings from very low light levels or weak pulse amplitudes that have affected earlier monitors using forehead reflectance sensors seem unlikely in these data because the reading reliability and accuracy was otherwise relatively consistent. The observed waveform morphology in many (although not all) instances was consistent with previous observations of “venous pulsations” when no applied pressures are used, and similarly improved when the headband was applied.14 Further testing that includes observations made at lower SaO2 levels may help elucidate the actual source of the artifacts.

Additional work must be conducted in the general patient population to observe the effects of mild pressure against the forehead sensor using the headband, especially in patients undergoing anesthesia or receiving vasoactive drugs. Published patient studies of forehead sensors that include headband use suggest that performance is improved compared with reading reliability when the headband is not; however, these studies did not specifically target venous pulsation environments.

Based on the results of our study, we conclude that use of the headband at 10–20 mmHg pressure with the forehead sensor decreases the occurrence of erroneous SpO2 readings and improves the performance of the sensor especially in patients in whom venous pulsations are most likely to occur. Our data also suggest that application of the headband before presence of venous pooling may be most effective.

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References