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Correlation between Pulse Oximetry Oxygen Saturation (SpO_2) and Measured Arterial Oxygen Saturation (SaO_2) and Arterial Oxygen Tension (PaO_2) in Neonates

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=Abstract=**Pulse oximetry has recently been introduced as a method for continuous and non-invasive transcutaneous monitoring of arterial oxygen saturation in neonates. The purpose of our study was to determine the reliability, accuracy, and practicability of pulse oximetry for monitoring arterial oxygenation in sick newborn infants. Pulse oximetry oxygen saturation values (SpO_2) were compared with simultaneously measured arterial oxygen saturation values (SaO_2) by a co-oximeter. The linear regression equation for 65 data pairs was $Y=24.53+0.726X$ ($r=0.90$, $p<0.01$). The difference between measured SaO_2 and pulse oximetry oxygen saturation (SpO_2) was 0.44% ± 2.97% (mean ± S.D.). The linear regression equation comparing measured SaO_2 minus pulse oximetry saturation (SpO_2) was $Y=-23.09+0.258X$ ($r=0.58$, $p<0.01$). This demonstrated an increasing error of pulse oximetry with decreasing SaO_2. Pulse oximetry oxygen saturation (SpO_2) also correlated well with measured arterial oxygen tension (PaO_2), and the upper reach of the S-shaped hemoglobin-oxygen dissociation curve was clear. With a hypothetical alarm limit set at 92%, all hyperoxemic values (29/29) were correctly identified (sensitivity 100%). Of the 78 paired values, 33 were classified correctly as nonhyperoxemic (specificity 42%), and a total of 62 (29 + 33) out of the 107 paired values were ranged correctly (accuracy 58%). The accuracy increased significantly with an increase in alarm limit up to 94%, and it remained stable thereafter.**

We conclude that pulse oximetry is a simple, accurate, noninvasive, and continuous method of transcutaneously measuring arterial oxygen saturation, and hyperoxemia can be detected by pulse oximetry with a high sensitivity provided that prior to use, type-specific alarm limits are set.

Key Words: *Pulse Oximetry, Oxygen Saturation, Neonate*

INTRODUCTION

Monitoring of blood oxygenation is fundamental in the assessment and management of the critically ill patient. Until now, arterial blood gas analysis was the only reliable means available to provide this information to clinicians. However, several pro-

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blems exist with the use of arterial blood gas measurements only: the measurement requires an invasive procedure, intermittent sampling may miss sudden changes, a considerable lag time may exist between ordering the test and obtaining the result, and deterioration in arterial blood gas measurements may occur relatively late in the evolution of respiratory failure (Narins and Emmet, 1980; Tobin, 1988; Tobin, 1989; Shapiro and Cane, 1989).

The continuous monitoring of arterial oxygenation is very important for the management of critically ill newborn infants in neonatal intensive care units (NICU). Transcutaneous oxygen tension ($TcPO_2$) monitoring, the most widely used method, demonstrates wide fluctuations in oxygen tension that cannot be detected by intermittent sampling of arterial blood (Peabody *et al.* 1978). Transcutaneous PO_2 monitoring permits rapid detection of hypoxemia associated with apnea, hypoventilation, or other procedures (Peabody., 1979; Long *et al.* 1980). However, transcutaneous PO_2 monitoring has serious limitations including frequent calibration periods and a heated electrode which causes first- and, occasionally, second-degree burns (Golden, 1981). Furthermore, unpredictable gradients have been reported between skin and arterial PO_2 values in older infants and in infants with bronchopulmonary dysplasia (Emery and Peabody, 1983; Rome *et al.* 1984).

Pulse oximetry, a newly developed technique, has been proposed as a noninvasive continuous method for transcutaneous monitoring of arterial oxygen saturation of hemoglobin in the newborn infants. But the reliability of this technique in detecting hyperoxemia is still controversial, because small changes in saturations greater than 90% are associated with relatively large changes in arterial oxygen tension (PaO_2).

The purpose of our study was to determine the reliability, accuracy, and practicability of pulse oximetry for monitoring arterial oxygenation in sick newborn infants. We studied the correlation between pulse oximetry oxygen saturation values (SpO_2) and measured arterial oxygen saturation values (SaO_2) by a co-oximeter and measured arterial oxygen tension values (PaO_2) in 14 sick neonates. And we also assessed the reliability of pulse oximetry using a hypothetical alarm limit of 92% SpO_2 in detecting hyperoxemia (defined as PaO_2 > 100 mmHg) and examined the effect of various alarm limits on its reliability.

MATERIALS AND METHODS

This study was performed in the Newborn Intensive Care Unit (NICU) at Seoul National University Children's Hospital (SNUCH) between January and September In 1989. 14 neonates who required mechanical ventilation and had indwelling arterial lines were included in this study. The causes for intubation and mechanical ventilation were respiratory distress syndrome (10 patients), meconium aspiration syndrome (2 patients), and recurrent apnea (2 patients). Additional clinical profiles are given in Table 1.

The pulse oximetry used in this study was the Ohmeda Biox 3700 (Ohmeda, Boulder Co.). The sensor was attached to a foot if an umbilical catheter was in place or on the ipsilateral hand if a radial catheter was in place. The sensor was shielded if phototherapy lights or radiant warmers in use.

Pulse oximetry arterial oxygen saturation values were recorded only when the pulse rate was less than 5 beats different from the heart rate on an independent bedside ECG monitor for at least 30 seconds. A pulse oximetry reading was measured when an arterial blood sample was simultaneously obtained for clinical management.

Arterial blood gas values were measured with a Radiometer ABL 30 Acid-Base Analyzer (Radiometer, Copenhagen) and SaO_2 with an IL 282 CO-Oximeter (Instrumentation Laboratory, Inc., Lexington, Mass.). SaO_2 (percent oxyhemoglobin) was measured for the total hemoglobin content, and values were corrected for fictitiously elevated carboxyhemoglobin, as suggested by Cornelissen *et al.* (1983), (1) %HbCO (fictitious) = 0.054 X $\%SaO_2$ (measured) + 0.24%, (2) $\%SaO_2$ (correct) = $\%SaO_2$ (measured) + %HbCO (fictitious). Results were expressed as the mean ± S.D., and data were analyzed using linear regression models and paired t-tests.

The reliability of pulse oximetry in detecting hyperoxemia was also assessed, and the effect

of various alarm limits on its reliability was examined. For the analysis, the PaO_2 values were regarded as the standard against which the pulse oximetry oxygen saturation values were compared. Hyperoxemia was defined as PaO_2 greater than 100 mmHg and pulse oximetry oxygen saturation (SpO_2) greater than 92% saturation. Every paired values was then classified in a 2 X 2 table as true hyperoxemia (PaO_2 > 100 mmHg and SpO_2 > 92%), true nonhyperoxemia (PaO_2 < 100 mmHg and SpO_2 < 92%), false hyperoxemia (PaO_2 < 100 mmHg and SpO_2 > 92%), or false nonhyperoxemia (PaO_2 > 100 mmHg and SpO_2 < 92%). Sensitivity (the proportion of hyperoxemia values correctly classified by pulse oximetry), specificity (the proportion of nonhyperoxemic values correctly classified by pulse oximetry), and accuracy (the proportion of values correctly classified hyperoxemic or nonhyperoxemic by pulse oximetry) were plotted against the hypothetical alarm limit to determine the optimal cut-off point. Optimal was defined as maximal specificity with a sensitivity of 95%.

RESULTS

The sensor was easily applied to a hand or foot in all instances, even in the smallest infant who weighed 680 gm, and the pulse oximetry oxygen saturation readings (SpO_2) remained functional over a wide range of hematocrit, bilirubin, and mean arterial blood pressure (Table 1). Similarly, pulse oximetry oxygen saturation readings (SpO_2) were not affected over a wide range of PaO_2, $PaCO_2$, and pH (Table 2).

Table 1. Clinical profiles of patients

	Mean ± SD	Range
Birth weight(gm)	1888 ± 1118	680 – 3660
Gestational age(wk)	32.0 ± 5.4	26 – 42
Hematocrit(%)	46.3 ± 8.5	29 – 65
Total bilirubin(mg/dl)	7.1 ± 3.1	2.4 – 15.3
Body temperature(℃)	34.9 ± 2.2	31.9 – 37.4
MAP(mmHg)*	45.6 ± 97	29 – 67

* MAP : mean arterial pressure

65 data pairs were available for comparing SpO_2 determined by the pulse oximetry and SaO_2 by the co-oximeter. The linear regression equation comparing pulse oximetry oxygen saturation

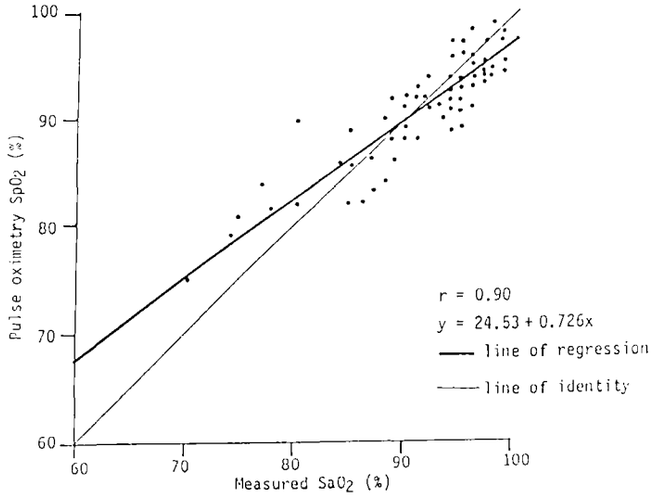

Fig. 1. Relationship between measured SaO_2 and pulse oximetry SpO_2.

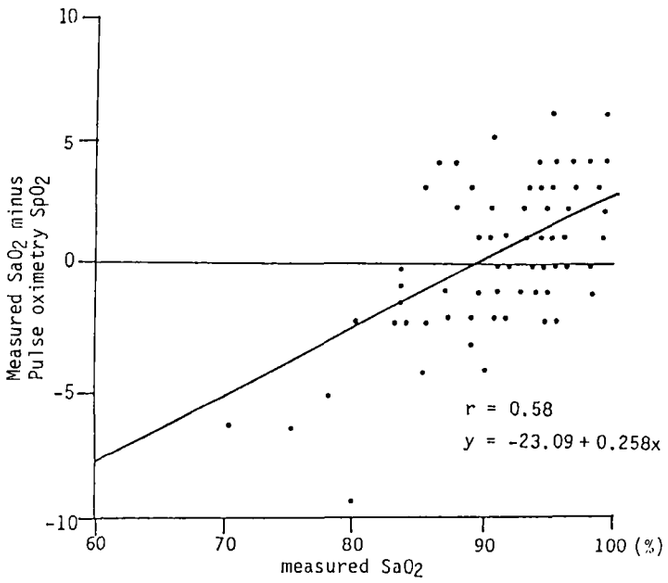

Fig. 2. Relationship between measured SaO_2 and error of pulse oximetry SpO_2.

Table 2. Blood gas analyses

	Mean ± SD	Range
PaO_2(mmHg)	86.4 ± 112.3	28 – 158
$PaCO_2$(mmHg)	45.7 ± 12.6	22 – 78
pH	7.31 ± 0.09	7.04 – 7.53
SaO_2(%)	88.3 ± 7.5	70 – 99
Carboxyhemoglobin(%)	6.5 ± 1.6	2.1 – 8.9

Table 3. Pulse oximetry oxygen saturation values associated with various levels of oxygen tension

PaO_2(mmHg)	No. of Measurements	Pulse Oximeter Mean ± SD	Saturation(%)
〉 100	29	96.1 ± 1.9	92 — 99
81 ~ 100	27	94.9 ± 2.6	87 — 99
50 ~ 80	39	90.7 ± 3.3	80 — 97
〈 50	12	77.9 ± 7.1	70 — 89

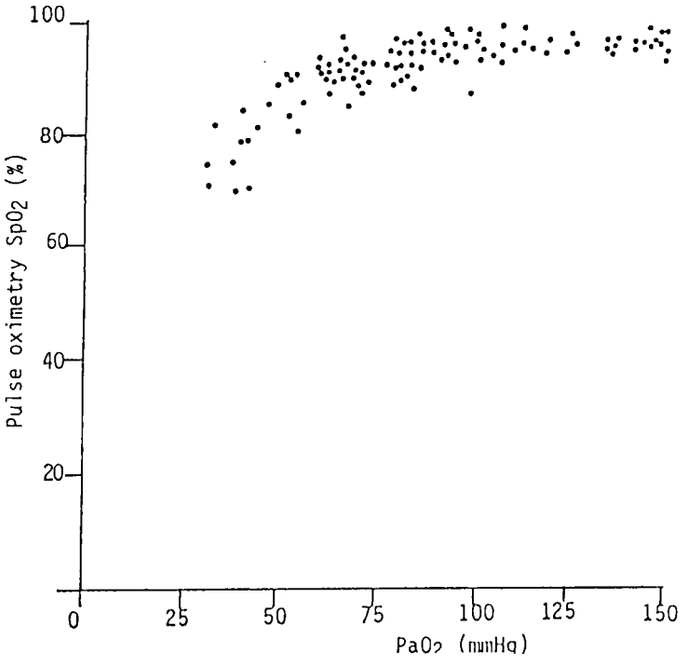

Fig. 3. Oxygen dissociation curve of study group generated by plotting each PaO_2 against its corresponding pulse oximetry SpO_2.

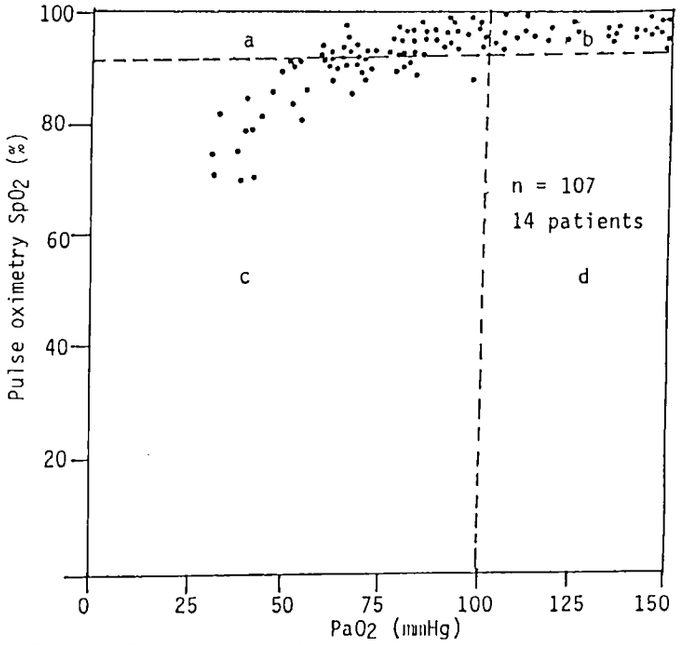

Fig. 4. Comparison of pulse oximetry SpO_2 with arterial oxygen tension (PaO_2). Cut-off lines are drawn at 92% for pulse oximetry SpO_2 and at 100 mmHg, for PaO_2, ranging the points as false hyperoxemia (a=45), true hyperoxemia (b=29), true nonhyperoxemia (c=33), or false nonhyperoxemia (d=0).

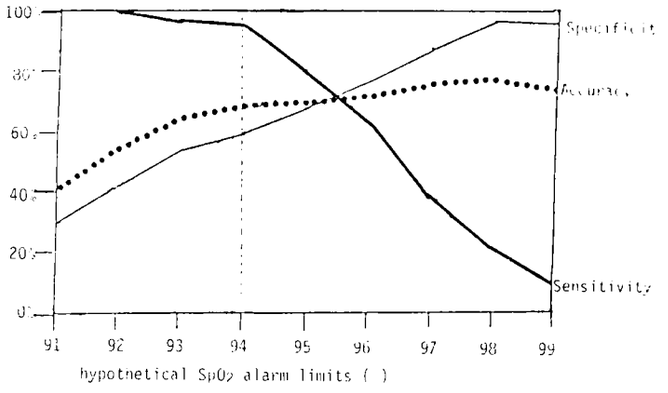

Fig. 5. Sensitivity (—), specificity (—), and accuracy (···) in detecting hyperoxemia (PaO_2 〉 100 mmHg) for hypothetical alarm limits of pulse oximetry SpO_2.

(SpO_2) with measured SaO_2 was Y = 24.53 + 0.726X (r=0.90, p 〈 0.01) (Fig. 1). The difference between measured SaO_2 and pulse oximetry oxygen saturation (SpO_2) was 0.44% ± 2.97% (mean ± S.D.). The linear regression equation comparing measured SaO_2 with measured SaO_2 minus pulse oximetry oxygen saturation (SpO_2) was Y = -23.09 + 0.258X (r=0.58, p 〈 0.01) (Fig. 2). This demonstrates an increasing error of pulse oximetry with decreasing SaO_2.

In order to compare PaO_2 with pulse oximetry oxygen saturation (SpO_2), 107 data pairs were available. The relation between PaO_2 and pulse oximetry oxygen saturation (SpO_2) is shown in Fig. 3, and the upper reach of the S-shaped hemoglobin-oxygen dissociation curve is clear.

In 29 data pairs, PaO_2 was in the hyperoxemic range (PaO_2 〉 100 mmHg) and SpO_2 was

96.1% ± 1.9% (mean ± S.D.) (Table 3). To assess the reliability of pulse oximetry in detecting hyperoxemia, the cut-off lines were drawn at 92% for pulse oximetry oxygen saturation (SpO_2) and at 100 mmHg for PaO_2 (Fig. 4).

With an alarm limit set at 92%, all hyperoxemic values (29/29) were correctly identified (sensitivity 100%). Of the 78 paired values, 33 were classified correctly as nonhyperoxemic (specificity 42%), and a total of 62 (29+33) of the 107 paired values were ranged correctly (accuracy 58%).

The dependence of sensitivity, specificity, and accuracy on the alarm limit is shown in Fig. 5. Accuracy increased significantly with increasing alarm limits up to 94%, and it remained stable thereafter.

DISCUSSION

Significant improvements in arterial oxygen monitoring have occurred over the last decade based on both technologic advances and a better understanding of the pathophysiologic characteristics of respiratory failure (Tobin, 1988). The major goals of monitoring are to provide alarms that alert the patient's attendants of a significant change in his condition, providing an opportunity for the timely institution of lifesaving measures, to aid with diagnosis and therapy, and to create trends that assist in assessing therapeutic response and predicting prognosis.

Arterial oxygen tension by analysis of arterial blood gases (PaO_2) has been the only reliable means available of providing the information to clinicians. However, the invasiveness of this technique, the time and skill required, and provision of only intermittent assessment are limitations of this traditional method.

In the early 1970's, the first successful use of transcutaneous measurement of arterial oxygen tension ($TcPO_2$) was reported (Huch *et al.* 1972). In the mid 1980's, most neonatal intensive care units in the United States had used transcutaneous arterial oxygen ($TcPO_2$) monitors as parts of the routine monitoring of critically ill newborn infants (Peabody and Emery, 1985). The reason for this rapid progression lies in the inadequacy of intermittent blood gas samples to assess the respiratory status of sick newborns and in the multiple complications reported from more invasive techniques (Stavis and Krauss, 1980). More recently, sensors have been developed for the assessment of carbon dioxide ($TcPCO_2$) across human skin (Severinghaus *et al.* 1978; Hansen and Tooley, 1979), but they also have some drawbacks. As summarized in a recent evaluation of transcutaneous monitors (Mosenkis, 1983), their values do not directly reflect actual measured arterial values. In addition, $TcPO_2$ monitors generally overestimate hypoxemia and underestimate hyperoxemia; need complicated set-up skill and a long calibration time; and carry a significant risk of burns associated with cutaneous heating, which is required to increase blood flow in the region of the sensor (Vidyasagar, 1984).

Deckardt and Steward (1984) report that continuous, noninvasive, transcutaneous oxygen saturation (SpO_2) is easier to measure and correlates well with in vivo hemoglobin saturation measurements (SaO_2) in preterm infants and is valuable because it indicates the status of the blood flow to vital organs and oxygen-carrying capacity of the blood. Because of the ease of application and physiologic advantages, pulse oximetry is being used, not only in neonatal intensive care units (NICU) but also as routine intraoperative monitoring of infant (Dziedzic and Vidyasagar, 1989).

The first devices to measure oxygen saturation through tissues were developed independently by Matthew and Kramer in 1935. Matthew used 2 wavelengths of light to distinguish between oxyhemoglobin and deoxyhemoglobin and is considered the forefather of pulse oximetry (Severinghaus, 1987). The devices used by them were large and not very practical for clinical use.

Pulse oximetry that we are familiar with today was made possible by development of microprocessors and light-emitting diodes. Clinical applications of modern pulse oximetry were originally reported by Nakajima (1975) in Japan. Sarnquist *et al.* (1980) were the first to report its use in the United States. Yelderman and New (1983) also tested uses of pulse oximetry and published results in 1983. Since their study, pulse oximetry has grown in popularity for the clinical management of patients and research activities.

Oxygen bound to hemoglobin (HbO_2) and dissolveded oxygen in plasma (O_2) are in a dynamic equilibrium, with HbO_2 being the favored form of the reaction. Approximately 98% to 99% of the oxygen in the blood is bound to hemoglobin and the remainder is dissolved in the plasma, which is measured as PaO_2. PaO_2 reflects dissolved oxygen not bound to hemoglobin. The oxygen-hemoglobin dissociation curve is a graphic representation of the equilibrium between the partial pressure of oxygen in the blood and the oxygen bound to the hemoglobin. This curve shifts in response to various physiologic factors, which are types of hemoglobin, temperature, pH, and 2,3-diphosphoglycerate (DPG) (Benesch and Benesch, 1967; Orzalesi and Hey, 1971). Fetal hemoglobin, high pH (alkalosis), hypothermia, and increased red blood cell levels of 2,3-DPG shift the curve to the left, which indicates an increased oxygen affinity, which leads to a decreased oxygen release to the tissue because of a more favored binding to hemoglobin. Adult hemoglobin, low pH (acidosis), hyperthermia, and decreased red blood cell levels of 2,3-DPG shift the curve to the right, which indicates a decreased oxygen affinity, which leads to an increased amount of oxygen available for tissue uptake. Current interpretation of oxygen saturation readings requires a better understanding of physiologic factors that influence the relationship of PaO_2 and SaO_2. In newborn infants with fetal hemoglobin, the oxygen dissociation curve shifts to the left, the steep portion of which indicates tissue extraction of large amounts of oxygen with a minimal drop in PaO_2. Therefore, a newborn infant may drop its PaO_2 from 80 mmHg to 40 mmHg without drastically affecting the oxygen saturation (Smith and Nelson, 1976). Oxygen saturation is an indication of the oxygen content of the blood, which is physiologically a more important factor.

Pulse oximetry uses techniques based on the principles of plethysmography and spectrophotometry (Yoshiya *et al.* 1980). Plethysmography is used to determine pulse amplitude and pulse waveform, whereas spectrophotometry is used to analyze the transmission of light through the tissues. Spectrophotometry is based on the assumption that oxyhemoglobin is red and deoxyhemoglobin is blue. The red and infrared light of a specific frequency is transmitted alternately from the transducer through a pulsating arterial bed to the photodetector. Red (660 nm) and infrared (940 nm) light is absorbed selectively by oxyhemoglobin (infrared) and deoxyhemoglobin (red). Deoxyhemoglobin absorbs red light and oxyhemoglobin transmits red light. The reverse is true for infrared light. During systole, the pulse-added absorbance is measured and empirically correlated to the preset in vivo arterial saturation data. The percentage of oxygen saturation is then calculated using the empirically-derived algorithms by a microprocessor in the monitor, using the simplified equation: percent oxygen saturation = (oxyhemoglobin/oxyhemoglobin + deoxyhemoglobin) X 100.

Like the reports of other investigators (Deckardt and Steward, 1984; New, 1985; Durand and Ramanathan, 1986; Harris *et al.* 1986; Ramanathan *et al.* 1987; Jennis and Peabody, 1987; House *et al.* 1987; Fanconi, 1988), our data demonstrated that the linear relationship between simultaneous pulse oximetry SpO_2 and measured SaO_2 by co-oximeter was good ($r=0.9$). When linear regression analysis of SaO_2 versus SaO_2 minus SpO_2 was conducted, a correlation coefficient of 0.58 was obtained, suggesting an increased error of pulse oximetry with decreasing SaO_2. The reasons for the differences in pulse oximetry SpO_2 value seen with highly saturated fetal hemoglobin cannot be readily explained. The reliability of spectrophotometric techniques for the measurement of saturation in newborn infants has been questioned (Zwart *et al.* 1981; Huch *et al.* 1983). The IL 282 CO-Oximeter used for arterial saturation measurements in our study is a four-wavelength spectrophotometer. Zwart *et al.* (1981) report falsely low oxyhemoglobin and falsely elevated carboxyhemoglobin readings when the IL 282 CO-Oximeter was used for SaO_2 measurements of blood containing fetal hemoglobin. These artifacts were related to slight differences in the absorption characteristics of fetal and adult hemoglobin for the wavelengths used by IL 282 CO-Oximeter. Cornelissen *et al.* (1983) reported a practical correction for these errors. Therefore, we used it for the correction of fictitiously-elevated carboxyhemoglobin: (1) %HbCO (fictitious) = 0.054 X %SaO_2 (measured)

+ 0.24%, (2) %SaO_2 (correct) = %SaO_2 (measured) + %HbCO.

A comparison of pulse oximetry SpO_2 values with arterial blood oxygen tension (PaO_2) values was done to test the capacity of SpO_2 to accurately predict PaO_2. Although similar estimates can be derived from other published data (Deckardt and Steward, 1984; Fanconi *et al.* 1985; Mok *et al.* 1986; Jennis and Peabody, 1987; Ramanathan *et al.* 1987), our analysis is important in identifying quantitatively the SpO_2 for prediction of PaO_2.

One serious drawback of pulse oximetry is its potential inaccuracy in detecting hyperoxemia. The reliability of this technique in detecting hyperoxemia is still controversial, because small changes in saturation greater than 90% are associated with relatively large changes in arterial oxygen tension (PaO_2). We used a dichotomous method (2 X 2 table) to analyze our results because that method corresponds best to the clinical practice in which alarm limits have to be set as cut-off points (Bucher *et al.* 1989). Both sensitivity and specificity depend on the alarm limit (Stemple, 1982). In our study, cut-off lines were drawn at 92% for pulse oximetry SpO_2 and at 100 mmHg for PaO_2. With a hypothetical alarm limit set at 92% SpO_2 in detecting hyperoxemia (defined as PaO_2 > 100 mmHg), all hyperoxemic values (29/29) were correctly identified (sensitivity 100%). Of the 78 paired values, 33 were classified correctly as nonhyperoxemic (secificity 42%), and a total of 62 (29+33) out of 107 paired values were ranged correctly (accuracy 58%). Sensitivity can be increased by decreasing the alarm limit, but the specificity is then decreased. If the aim of monitoring oxygenation is to avoid hyperoxemia, a high sensitivity is more important than a high specificity. With a minimal sensitivity of 95%, accuracy (69%) increased significantly with increased alarm limits up to 94%, and it remained stable thereafter. Maximal specificity was 60%. The optimal alarm limit, defined as maximal specificity with a sensitivity of 95%, was 94% in our analysis.

We concluded that pulse oximetry is a simple, accurate, noninvasive, and continuous method of transcutaneously measuring arterial oxygen saturation, and hyperoxemia can be detected by pulse oximetry with high sensitivity provided that, prior to use, type-specific alarm limits are set.

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=국 문 초 록=

신생아에서 Pulse Oximetry에 의한 산소포화도(SpO_2)와 동맥혈 산소포화도(SaO_2) 및 동맥혈 산소분압(PaO_2)의 상관관계

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최근 pulse oximetry가 신생아에서 경피적, 비침습적, 계속적인 동맥혈 산소포화도 측정방법으로 소개되었다. 저자들은 호흡곤란이 있는 신생아에서 동맥혈 산소화 정도를 측정하는 데 있어서의 pulse oximetry의 신빙도, 정확도 및 실용도를 알아보고자 하였다.

Pulse oximetry에 의해 측정된 산소포화도치(SpO_2)와 동시에 CO-Oximeter로 측정한 동맥혈 산소포화도치 (SaO_2)를 14명의 신생아에서 얻은 65쌍의 data를 이용하여 비교한 결과, $Y = 24.53 + 0.726X$의 직선 회귀 방정식의 높은 상관관계($r=0.9$, $p < 0.01$)를 보였다. 동맥혈 산소포화도치(SaO_2)와 pulse oximetry로 측정한 산소포화도치(SpO_2)의 차는 0.44% ± 2.97%(평균 ± 표준편차)이었으며, 동맥혈 산소포화도치(SaO_2)와 동맥혈 산소포화도치에서 pulse oximetry로 측정한 산소포화도치를 뺀 값($SaO_2 - SpO_2$)을 비교한 결과 $Y = -23.09 + 0.258X$의 직선 회귀 방정식의 상관관계($r=0.58$, $p < 0.01$)가 있었다. 이것은 동맥혈 산소포화도치(SaO_2)가 낮아질수록 pulse oximetry로 측정한 산소포화도치(SpO_2)의 오차가 커짐을 보여주었다. Pulse oximetry로 측정한 산소포화도치(SpO_2)와 동맥혈 산소분압(PaO_2)을 비교했을 때도 높은 상관관계가 있었으며, S-자 헤모글로빈-산소 해리 곡선의 상부에서 뚜렷하였다.

가상의 경보한계치(alarm limit)를 92%에 설정했을 때, 고산소혈증치를 보인 경우는 29/29로 감수성(sensitivity)이 100%이었고, 비-고산소혈증을 보인 경우는 33/78로 특이성(specificity)이 42%이었으며, 정확도(accuracy)는 58%이었다. 95%의 감수성에서 최대의 특이성(60%)을 보였을 때의 경보한계치는 94%이었고, 이 경우 정확도는 69%로 의미 있게 높아졌다.

이상의 연구에서, 저자들은 최근에 소개된 pulse oximetry가 간단하고 정확하며, 비침습적 계속적 경피적인 동맥혈 산소포화도 측정방법이며, 사용 전에 기계에 따른 경보한계선을 설정함으로써 높은 감수성으로 고산소혈증을 찾아낼 수 있다는 결론에 도달하였다.