Validity of pulse oximetry in detection of hypoxaemia in children: comparison of ear, thumb and toe probe placements

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مدى موثوقية قياس التأكسج النبضي في كشف نقص أكسجة الدم لدى الأطفال: مقارنة بين مواضع المسبار في الأذن و إبهام اليد وإبهام القدم

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الخلاصـة: أجريت هذه الدراسة على المرض من الولدان في الرعاية المركزة، واستهدفت التعرف على المواضع التي ينبغي وضع المسبار لقياس التأكسج النبضي فيها للحصول على أكثرها دقة وموثوقية من حيث قراءات نتائج التشبع المحيطي بالأكسجين. وقد استخدم الباحثون تحليل غازات الدم، واعتبروها معياراً ذهبياً، كما اعتبروا التشبع المحيطي بالأكسجين الذي يقل عن (92٪) وتشبع الدم بالأكسجين عند تحليل غازات الدم والذي يقل عن (90٪) مؤشرين على نقص أكسجة الدم، فوجدوا أن القيم التنبؤية السلبية للتشبع المحيطي بالأكسجين عند وضع المسبار بإبهام القدم (98٪)، وذلك لدى 110 طفلاً، وأن القيم التنبؤية السلبية للتشبع المحيطي بالأكسجين بلغت (93٪) في جميع المواضع الثلاث (الأذن وإبهام اليد وإبهام القدم) لدى 90 وليداً. وقد كان أعلى مستوى من التوافق السريري بين قيم التشبع المحيطي بالأكسجين وتشبع الدم بالأكسجين عند تحليل غازات الدم المحيطي عند وضع المسبار في الأذن (إذ بلغت قيمة كابا 0.70 لدى الأطفال و0.54 لدى الولدان)، وكان ذلك التوافق في أدنى مستوى له عند وضع المسبار في إبهام القدم (قيمة كابا 0.57 لدى الأطفال و0.28 لدى الولدان).

ABSTRACT This study of paediatric intensive care patients aimed to determine where pulse oximetry probes should be placed to obtain the most accurate and reliable readings of peripheral oxygen saturation (SpO_2). Using arterial blood gas analysis (SaO_2) as the gold standard and SpO_2 < 92% and SaO_2 < 90% as indicators of hypoxaemia, negative predictive values of SpO_2 were 96%, 98% and 98% at the ear, thumb and big toe respectively in 110 children, and 93% at all 3 sites in 90 neonates. The highest clinical agreement between SaO_2 and SpO_2 was for ear probes in children (κ = 0.70) and the lowest was for big toe probes (κ = 0.57 and 0.28 in children and neonates respectively).

Validité de l'oxymétrie de pouls pour détecter l'hypoxémie chez l'enfant : comparaison du placement de la sonde au niveau de l'oreille, du pouce et de l'orteil

RÉSUMÉ La présente étude sur les patients en soins intensifs néonataux a pour objectif de définir l'emplacement de la sonde oxymétrique afin d'obtenir les relevés les plus fiables et les plus précis de la saturation en oxygène (SpO_2). En utilisant l'analyse des gaz du sang artériel (SaO_2) comme méthode de référence associée à une SpO_2 < 92 % et à une SaO_2 < 90 % comme indicateurs d'hypoxémie, les valeurs prédictives négatives de SpO_2 étaient de 96 %, 98 % et 98 % au niveau de l'oreille, du pouce et du gros orteil, respectivement chez 110 enfants, et de 93 % aux trois endroits chez 90 nouveau-nés. La sonde auriculaire a permis d'obtenir la meilleure corrélation clinique entre la SaO_2 et la SpO_2 chez l'enfant (κ= 0,70) alors que la sonde au niveau du gros orteil a recueilli les moins bons résultats (κ = 0,57 et 0,28, chez l'enfant et le nouveau-né respectivement).

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Introduction

Pulse oximetry is a noninvasive technique of measuring oxygenation of the blood that is used worldwide to assess critically ill patients, especially in intensive care units and operating rooms. Its advantages include the early detection of hypoxia and hyperoxia, less frequent need for blood sampling for blood gas analysis, determination of the required fraction of inspiratory O_2 and support for the process of ventilator weaning [1–3]. The use of pulse oximetry in the operating room has revealed that preoperative hypoxaemia is much more prevalent than was previously supposed [4] and, although there is no definitive evidence, the generalized use of pulse oximetry may have contributed to decreased morbidity and mortality rates of the preoperative period.

Monitoring of peripheral oxygen saturation (SpO_2) by pulse oximetry can be done either continuously or intermittently (spot check) depending on the clinical status of the patient [5]. All types of pulse oximeters operate on the Beer–Lambert law of spectral analysis based on light absorption [6,7]. The performance of the pulse oximeter can be disrupted by several factors including: poor peripheral perfusion, peripheral vasoconstriction, hypotension, low pulse pressure and patient's motion [8]. In clinical practice, many sites are used for pulse oximetry probe placement, including the nasal septum, ear lobe, thumb and big toe. A study on 13 adult patients showed that significant delays in the detection of acute hypoxaemia by pulse oximetry occurred when the probe was placed at the toe compared with probes at either the ear or finger [9].

We could not find any similar study in the available medical literature to determine the most appropriate site for pulse oximetry probe placement in newborns and children. This study was therefore designed to evaluate simultaneous SpO_2 levels recorded by pulse oximetry from probes placed on ear, thumb and big toe of paediatric patients and to compare the validity of the results with arterial blood gas (ABG) analysis.

Methods

In this cross-sectional comparative study we compared the readings from 3 different types of pulse oximetry probes/placements (ear, thumb and big toe) and assessed their validity in detecting hypoxaemia by comparing the results with those of ABG analysis as the gold standard for diagnosis of blood gas disorders.

Sample

The sample was 200 paediatric patients: 90 newborn infants (aged < 1 month) and 110 children (aged 1+ months). Sampling was done by a simple consecutive method covering all patients who were admitted to the paediatric intensive care unit (PICU) or neonatal intensive care unit (NICU) of Tabriz Children's Hospital during a 1-year period from 1 November 2004 to 31 October 2005. Of the 216 children admitted, we enrolled only 200 in the study who needed simultaneous blood sampling for ABG analysis and pulse oximetry during their treatment. Therefore no children underwent unnecessary blood sampling or any other test for completion of the study. We also excluded those patients whose tests were suggestive of a technical error. Therefore 16 children were finally excluded from this study.

Data collection

The Novametrix pulse oximeter (Novametrix Medical Systems, Connecticut, USA) and GEM-3000 blood gas analyser (Instrumentation Laboratory, Massachusetts, USA) were used. For blood gas analysis, arterial blood was drawn from radial or brachial arteries, and international standard laboratory protocols for blood gas sampling, sample transport and analysis were adhered to.

Pulse oximetry was recorded simultaneously on 3 different probe placement sites in each patient (ear, thumb and big toe) by a trained nurse or a paediatric resident using a specially structured probe for each site.

The research review board and ethics committee of Tabriz University of Medical Sciences approved the study. However, the method imposed no additional cost or harm on participants and there was therefore no need to obtain special written permission from parents.

Analysis

The validity of pulse oximetry in the detection of hypoxaemia was determined by comparing the results with those of simultaneous ABG analysis (gold standard); $SpO_2 < 92\%$ and arterial oxyhaemoglobin saturation (SaO_2) < 90% were considered indicators of hypoxaemia in the study. Statistical analysis of data was done using standard formulae (sensitivity, specificity and positive and negative predictive values). The bias was calculated for both age groups (neonates and children) using the following equation: bias = $SpO_2 – SaO_2$. We also determined the accuracy of the bias, which is equal to the standard deviation (SD). Clinical agreement was calculated by the kappa test using the following cut-offs: $\kappa \leq 0.20$ (negligible or little agreement); $0.20 < \kappa \leq 0.40$ (minimal agreement); $0.40 < \kappa \leq 0.60$ (moderate agreement); $0.60 < \kappa \leq 0.80$ (good agreement); $\kappa > 0.80$ (excellent agreement).

Results

The mean age of the children was 42 (SD 40) months and of the neonates was 7.5 (SD 6.0) days. The mean haemoglobin level was 11.8 (SD 2.2) g/dL in children and 12.9 (SD 2.6) g/dL in neonates. The mean recorded values of SaO_2, SpO_2 and the bias in both groups are shown in Table 1. The mean SaO_2 was 94.6 (SD 2.3) and 94.4 (SD 3.0) in children and neonates, respectively.

Table 1 Mean recorded values of arterial oxyhaemoglobin saturation (SaO₂) by blood gas analysis and peripheral oxygen saturation (SpO₂) by pulse oximetry on 3 parts of the body in children and neonates

Age group	SaO_2 (mmHg)	SpO_2 (mmHg)			Bias (mmHg)		
		Ear	Thumb	Big toe	Ear	Thumb	Big toe
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Children	94.6 (2.3)	95.9 (3.1)	93.7 (3.3)	92.6 (5.4)	0.02 (3.71)	–0.82 (3.43)	–1.94 (3.18)
Neonates	94.4 (3.0)	96.8 (2.2)	95.4 (3.2)	94.8 (2.4)	1.53 (3.42)	0.22 (3.84)	–0.45 (3.90)

SD = standard deviation.

In the children the mean bias of pulse oximetry readings was 0.02 (SD 3.71), –0.82 (SD 3.43) and –1.94 (SD 3.18) at the ear, thumb and big toe respectively. In the neonates the mean bias of pulse oximetry was 1.53 (SD 3.42), 0.22 (SD 3.84) and –0.45 (SD 3.9) at the ear, thumb and big toe respectively.

The number of hypoxaemic cases detected by simultaneous pulse oximetry in the 3 parts of the body and ABG analysis in children and newborn infants are shown in Table 2. The sensitivity, specificity and positive and negative predictive values, as well as the results of the κ-test in children and newborn infants, are shown in Table 3. Sensitivity was 67%, 83% and 83% and specificity was 98%, 92% and 90% for probes at ear, thumb and big toe respectively. Negative predictive values of SpO₂ were 96%, 98% and 98% at the ear, thumb and big toe respectively in the children, and 93%

at all sites in the newborns. The highest clinical agreement between SaO₂ and SpO₂ was for ear probes (κ = 0.70 and 0.54 in children and neonates respectively) and the lowest was for big toe probes (κ = 0.57 and 0.28 respectively).

Discussion

The role of pulse oximetry in the early detection of hypoxaemia has been emphasized by many studies. Moller et al. revealed that hypoxaemia can be diagnosed in patients monitored by pulse oximetry 19 times more frequently than in those without it [10]. Progressive utilization of pulse oximetry especially in PICUs has not only resulted in more frequent and earlier detection of hypoxaemia, but also diminished the need for repetitive blood gas analysis and its associated cost and complications.

Our main goal was to determine where the pulse oximetry probes should be placed in patients admitted to the NICU and PICU to obtain the most accurate and reliable readings of SpO₂ compared with ABG as the gold standard. Our study showed that SpO₂ at the big toe had the lowest clinical agreement with SaO₂ in both neonates and children. This is similar to the findings of a previous study on healthy volunteers by Hamber et al., who noted that significant delays occurred in the detection of acute hypoxaemia by pulse oximetry when the probe was placed at the toe compared with probes at the ear or finger. They declared that if hypoxaemia is defined as SpO₂ < 90%, the mean delay time for detection of hypoxaemia was 6 seconds at the finger compared with the ear, 57 seconds at the finger compared with the toe and 63 seconds at the toe compared with the ear [9]. Conversely, Jensen, Onyskiw and Prasadclaimed that the results of pulse oximetry were more accurate at the finger in comparison with the ear [11]. Clayton et al. recommended finger probes in patients with hypoperfusion [12].

In Kelly McAlpine and Kyle's study at SpO₂ = 92%, sensitivity and specificity were reported to be 100% and 86% respectively (false negatives = 0); but at SpO₂ = 88% the sensitivity fell to 66.7% and specificity rose to 96.4% (false negatives = 33) [13]. Our study showed that at SpO₂ = 92% we can predict (in children) that SaO₂ will be ≥ 90% with a sensitivity of 67%, 83% and 83% aand a specificity of 98%, 92% and 90% by placing the pulse oximetry probes at ear, thumb and big toe, respectively.

Table 2 Number of hypoxaemic cases detected by simultaneous pulse oximetry on 3 parts of the body in children and neonates versus arterial blood gas (ABG) analysis as the gold standard

Age group/ probe site	Comparison of pulse oximetry versus ABG				Total
	True positives	True negatives	False positives	False negatives	
	No.	No.	No.	No.	No.
Children					
Ear	8	96	2	4	110
Thumb	10	90	8	2	110
Big toe	10	88	10	2	110
Neonates					
Ear	4	80	0	6	90
Thumb	6	76	2	6	90
Big toe	2	74	8	6	90

SpO₂ < 92% and SaO₂ < 90% were considered as indicators of hypoxaemia: true positive: both SpO₂ < 92% and SaO₂ < 90%; true negative: both SpO₂ ≥ 92% and SaO₂ ≥ 90%; false positive: SpO₂ < 92% but SaO₂ ≥ 90%; false negative: SpO₂ ≥ 92% but SaO₂ < 90%.

Table 3 Validity and clinical agreement of pulse oximetry readings on 3 parts of the body in children and neonates

Age group/ probe site	Sensitivity	Specificity	Positive predictive value	Negative predictive value	Clinical agreement (κ)
	%	%	%	%	
Children					
Ear	67	98	80	96	0.70
Thumb	83	92	56	98	0.62
Big toe	83	90	50	98	0.57
Neonates					
Ear	40	100	100	93	0.54
Thumb	50	97	75	93	0.55
Big toe	25	90	20	93	0.28

According to Bell et al.'s study, the result of the deduction $SpO_2–SaO_2$ was called the bias and the standard deviation for the deductions was named accuracy [14]. In the study of Uystepruyst et al. the amount of bias in general conditions was 2.1% but changed to 0.6% (SD 3.2%) when SaO_2 was > 90% [15]. It must be mentioned that bias can be negative as noted by Van de Louw et al. [–0.02 (SD 2.1)] [4]. The amount of bias in our study was 0.02 (SD 3.71) at the ear, –0.82 (SD 3.43 at the thumb and –1.94 (SD 3.18) at the big toe, which shows underestimation by the toe probe and to some extent by the finger probe, but relative overestimation by the ear probe. Besides, there were similar findings in the neonate group; bias was 1.53 (SD 3.42) at the ear and –0.45 (SD 3.90) at the toe. By considering $SpO_2 = 92\%$ in our study, the negative predictive value of the ear and thumb probes were 96% and 98% respectively in neonates and 93% and 93% respectively in children aged over 1 month. This means that in 96% to 98% of patients who show $SpO_2 \geq 92\%$, their SaO_2 will be $\geq 90\%$, and therefore they are not affected with hypoxaemia. Such findings were also noted in the study of Van de Louw et al., but by considering $SpO_2 = 94\%$, the negative predictive value was 99% [4]. This means that 99% of patients with $SpO_2 > 94\%$ would have $SaO_2 \geq 90\%$ and therefore no hypoxaemia.

One key result of our study was the low sensitivity and minimal to moderate clinical agreement of pulse oximetry with ABG in neonates. It raises the question whether the light absorption characteristics of neonatal tissues are different at $SpO_2 = 92\%$. The study of Uystepruyst et al. revealed that bias and accuracy are not affected by fetal haemoglobin because the light absorption characteristics of fetal haemoglobin for wavelengths of light used in usual pulse oximeters are similar to those of adult haemoglobin [15].

Conclusion

Our study showed that pulse oximetry at the toe had the lowest clinical agreement with ABG results in both neonates and children. However, when the probe was placed at the ear or finger of newborns or children, the result of pulse oximetry were more reliable for exclusion of hypoxaemia and correlated more closely with the ABG result. This means that 96% to 98% of patients who show $SpO_2 \geq 92\%$ at the ear or finger, their SaO_2 will be 90% or more, and therefore are not affected with hypoxaemia.

Acknowledgements

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Manual for the health care of children in humanitarian emergencies

This manual was developed based on the recommendations of a global technical consultation on child health in humanitarian emergencies co-organized by WHO and UNICEF at the end of 2003. It is a collaborative work of three technical areas within WHO: Child and Adolescent Health and Development (CAH), Health Action in Crises (HAC), and Disease Control in Humanitarian Emergencies (DCE).

The objective of the manual is to provide comprehensive guidance on child care in emergencies. Existing guidelines, such as IMCI, assume a functioning health system that facilitates the referral of children, which may not be available in emergency situations. So this manual also includes the initial management of severe conditions. It was also realized that existing manuals do not cover injuries, burns, neonatal illness, psychosocial problems etc, which are considered of high priority in emergency settings. These are addressed along with issues on mental health, psychosocial support and common preventive interventions such as immunization.

Each chapter summarizes the main ways of diagnosis, treatment and prevention using flow charts. The flow charts are arranged in such a way that they can be enlarged for use as job aids/wall charts, or for modular training at convenient times on the management of each condition.

The manual is available in English and French at: http://www.who.int/child_adolescent_health/documents/9789241596879/en/index.html