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Original Article

Accuracy of the Lifebox pulse oximeter during hypoxia in healthy volunteers

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Summary

Pulse oximetry is a standard of care during anaesthesia in high-income countries. However, 70% of operating environments in low- and middle-income countries have no pulse oximeter. The 'Lifebox' oximetry project set out to bridge this gap with an inexpensive oximeter meeting CE (European Conformity) and ISO (International Organization for Standardization) standards. To date, there are no performance-specific accuracy data on this instrument. The aim of this study was to establish whether the Lifebox pulse oximeter provides clinically reliable haemoglobin oxygen saturation (S_pO_2) readings meeting USA Food and Drug Administration 510(k) standards. Using healthy volunteers, inspired oxygen fraction was adjusted to produce arterial haemoglobin oxygen saturation (S_aO_2) readings between 71% and 100% measured with a multi-wavelength oximeter. Lifebox accuracy was expressed using bias ($S_pO_2 - S_aO_2$), precision (SD of the bias) and the root mean square error (Arms). Simultaneous readings of S_aO_2 and S_pO_2 in 57 subjects showed a mean (SD) bias of −0.41% (2.28%) and Arms 2.31%. The Lifebox pulse oximeter meets current USA Food and Drug Administration standards for accuracy, thus representing an inexpensive solution for patient monitoring without compromising standards.

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Pulse oximetry is widely accepted as a standard of care during anaesthesia in high-income countries. The American Society of Anesthesiologists (ASA), World Health Organization (WHO) and the World Federation of Societies of Anaesthesiologists (WFSA) all officially endorse the use of pulse oximetry during anaesthesia [1, 2]. However, recent studies have shown that pulse oximetry is still only available in 41–70% of operating environments in low- and middle-income countries compared with nearly 100% availability in high-income countries, representing a 'pulse oximetry gap' [3].

As part of a drive to improve anaesthesia safety throughout the world, the 'Lifebox' oximetry project operates in parallel to the WHO Safe Surgery Saves Lives initiative to provide a low-cost, high-quality pulse oximeter for low- and middle-income countries [4]. Lifebox is a non-profit organisation with founding funding from the Association of Anaesthetists of Great Britain & Ireland, and is registered as a charity in the UK. The mission of this charity is to place a pulse oximeter in every operating room in the world to "*preserve and protect the health of patients worldwide…*"

[5]. To fulfil its vision, the Lifebox programme set out to develop an oximeter that is durable, easy to use, low-maintenance, inexpensive and accurate. The final production model, the 'Lifebox Oximeter' (Acare Devices Model AH-MX Handheld Pulse Oximeter, Xinzhuang City, Taiwan), has been demonstrated to be effective in clinical use, as well as meeting CE and ISO 9919.2005 calibration standards [6]. However, to date, there have been no specific data on performance testing to the USA Food and Drug Administration (FDA) 510(k) standards.

We therefore set out to compare the performance and accuracy of the Lifebox pulse oximeter against arterial haemoglobin oxygen saturation (S_aO_2) measured with a multi-wavelength oximeter. Although performance testing is not required for marketing outside the USA, this allows a direct comparison between the Lifebox pulse oximeter and commercially available pulse oximeters being used in high-income countries.

Methods

The study was performed at two sites, University of California San Francisco (UCSF) and Duke University Medical Center (DUMC), using nearly identical protocols regularly implemented in these laboratories to test other new oximeter units for FDA 501(k) certification in the USA [7]. FDA standards require a root mean square error (Arms) < 3% over a saturation range of 70–100%. Informed written consent was obtained from all subjects. At UCSF, the Committee on Human Research approved the research and 23 healthy adult volunteer subjects of mixed sex and ethnicity were studied. At Duke University, with DUMC Institutional Review Board approval, 34 healthy volunteers were studied. The methods involved for producing steady-state levels of hypoxaemia were essentially identical between the centres.

Two Lifebox pulse oximeter units were tested on each subject. To assess consistency between different production models, one probe from each unit was placed on each middle finger of the subject to measure haemoglobin oxygen saturation (S_pO_2). A cannula was placed in the radial artery. Measurements of S_aO_2 were made using a multi-wavelength optical blood analyser, either the OSM-3 (Radiometer America Inc, Westlake, OH, USA) at UCSF or the Gem Premier Plus 4000 (Instrumentation Laboratories, Bedford, MA, USA) at DUMC.

At the beginning of every experiment, each subject had two arterial blood samples drawn while breathing room air. A hypoxic gas mixture containing nitrogen, oxygen and carbon dioxide was titrated to induce the desired level of steady-state hypoxaemia. This was controlled to produce different S_aO_2 levels between 70% and 100% on the basis of end-tidal gas analysis and a computer-calculated estimate of arterial saturation based on end-tidal gas analysis. We did not have access to the proprietary information regarding exact time averaging of the oximeters, so to allow for the averaging algorithm intrinsic to all pulse oximeters, each S_aO_2 level was maintained for at least 30 s until the pulse oximeter readings stabilised. At this point, two arterial blood samples were obtained approximately 30 s apart. The mean of these readings was calculated for comparison with S_pO_2.

Pulse oximeter accuracy was determined by calculating the bias ($S_pO_2 - S_aO_2$), precision (SD of the bias) and the Arms over different ranges of S_aO_2 as established for FDA 510(k) regulation of pulse oximeter performance. The limits of agreement were calculated compensating for repeated measurements on subjects. The effect of S_aO_2 on bias was analysed by linear regression, taking into account repeated measures. As the gas mixture was supplied using a facemask at UCSF and a mouthpiece at DUMC, and the oximeter instruments used for S_aO_2 measurements were different between the two centres, data were initially analysed separately to ensure homogeneity.

Data were analysed using JMP 10.0 (SAS Institute, Cary, NC, USA) and Excel 2011 (Microsoft Corporation, Redmond, WA, USA). For all statistical tests, a value of $p < 0.05$ was considered significant [8–10]. The effect of multiple comparisons was accounted for using the Tukey–Kramer procedure.

Results

At UCSF, 758 total comparisons were made between paired arterial blood sample and pulse oximeter readings from two Lifebox oximeters in 23 healthy volunteers. Data collected covered S_aO_2 readings from 60% to 100%. At DUMC, 744 comparisons were made in 34 healthy volunteers. The characteristics of the sub-

jects are shown in Table 1. Study subjects at UCSF were slightly older. Distributions of ethnicity were also slightly different, with no African American or Hispanic subjects in the DUMC group.

Table 1 Characteristics of the subjects at the two study centres. Values are mean (SD) or number (proportion).

	UCSF (n = 23)	DUMC (n = 34)
Age; years	26.0 (3.2)	23.1 (5.0)
Male	15 (65%)	18 (53%)
Ethnicity		
African American	3 (13%)	0
Asian	4 (18%)	7 (21%)
Caucasian	12 (57%)	27 (79%)
Hispanic	2 (10%)	0
Other/declined	2 (10%)	

UCSF, University of California San Francisco; DUMC, Duke University Medical Center.

There was no difference between the readings for the two oximeters used at UCSF, so the data were pooled. At UCSF, the mean (SD) bias was −0.36 (2.33) and the Arms was 2.36% for S_aO_2 71–100% (Table 2). Bias was slightly more positive at lower S_aO_2, but this effect was small (0.04% for every 1% difference in S_aO_2, $p < 0.0001$). For DUMC data, bias was −0.45 (2.23%), and the Arms 2.27%. The S_aO_2 did not affect the bias ($p = 0.68$); however, a higher proportion of readings for the Duke subjects were at S_aO_2 > 90%. After accounting for S_aO_2, the bias did not differ by institution ($p = 0.79$). The pooled data over the 71–100% saturation range, representing 1467 paired observations of pulse oximeter reading and S_aO_2 values, indicated a mean bias of −0.41%, a precision of 2.28% and Arms error of 2.31% (Table 2). Thirty-five observations were made in the S_aO_2 range 60–70%. These levels were not required by the FDA standards,

Table 2 Accuracy of the Lifebox pulse oximeter over different arterial saturation ranges.

	All					
S_aO_2 range	60–70%	71–80%	81–90%	91–100%	71–100%	60–100%
UCSF Lifebox #1						
n, paired observations	13	96	109	158	363	376
Mean bias (%)	1.13	0.41*	−0.70	−0.85	−0.47	−0.41
Precision (%)	2.49	2.16	2.24	1.44	1.97	2.01
Arms (%)	2.65	2.19	2.34	1.66	2.03	2.05
UCSF Lifebox #2						
n, paired observations	22	109	100	151	360	382
Mean bias (%)	0.40	0.83*	−0.52	−0.84	−0.24	−0.21
Precision (%)	3.21	2.77	3.25	1.71	2.64	2.67
Arms (%)	3.16	2.88	3.27	1.90	2.65	2.68
UCSF Lifebox, pooled						
n, paired observations	35	205	209	309	723	758
Mean bias (%)	0.67	0.63*	−0.61	−0.84	−0.36	−0.31
Precision (%)	2.95	2.51	2.76	1.57	2.33	2.37
Arms (%)	2.98	2.58	2.82	1.78	2.36	2.39
Duke lifebox						
n, paired observations	0	191	176	377	744	744
Mean bias (%)	N/A	−0.32	−0.68	−0.42	−0.45	−0.45
Precision (%)	N/A	3.12	2.53	1.37	2.23	2.23
Arms (%)	N/A	3.13	2.61	1.43	2.27	2.27
Pooled devices						
n, paired observations	35	396	385	686	1467	1502
Mean bias (%)	0.67	0.18*	−0.64	−0.61	−0.41	−0.38
Precision (%)	2.95	2.86	2.66	1.48	2.28	2.30
Arms (%)	2.98	2.86	2.73	1.60	2.31	2.33

S_aO_2, oxygen saturation measured by arterial blood sample; S_pO_2, arterial oxygen saturation measured by pulse oximetry; mean bias, average of the bias ($S_pO_2 - S_aO_2$) within the specified S_aO_2 range; precision, SD of the bias.
*$p < 0.0001$ compared with 81–90% and 91–100% ranges.

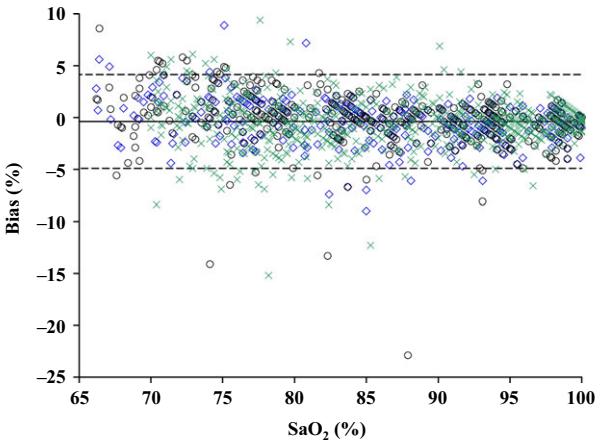

Figure 1 Bias% ($S_pO_2 - S_aO_2$) plotted against S_aO_2% for the Lifebox pulse oximeter. SpO_2, pulse oximeter oxygen saturation; S_aO_2, arterial oxygen saturation. (◇) UCSF oximeter #1; (○) UCSF oximeter #2; (×) DUMC; solid line, mean bias; dashed lines, upper and lower 95% limits of agreement.

but are included in Table 2 for the sake of completeness. Figure 1 shows bias for individual data points.

Discussion

The Lifebox pulse oximeter detects hypoxia in healthy volunteers at a degree of accuracy and bias that is comparable to FDA-approved pulse oximeters made by major manufacturers. This conclusion is based on data collected at two independent testing facilities (UCSF and DUMC), using similar protocols in healthy volunteers.

Our data confirm an acceptable level of accuracy for the Lifebox pulse oximeter when compared with a gold standard multi-wavelength oximeter measurement using arterial blood. Bias describes how the pulse oximeter measurement deviates from a gold standard, where a positive bias would indicate that the pulse oximeter reads high. Mean bias was less than 1% at all S_aO_2 ranges. However, poor precision (high SD) may be present together with low bias. The Arms statistic combines these two, and will be high if either the bias or SD is high. To meet FDA standards for pulse oximetry accuracy, the Arms value must be $< 3\%$. The Lifebox pulse oximeter met this standard over the range of S_aO_2 from 71% to 100%.

Although the data are not presented here, we also noted that the Lifebox unit performed equally well when compared with currently available commercial units in the USA.

Pulse oximetry is a recognised standard of care for anaesthetic monitoring in high-income countries. The Lifebox oximeter has been made available for distribution throughout low- and middle-income countries, where previously oximeters have not been readily available, to bridge the 'oximeter gap'. To achieve this goal, the Lifebox oximeter was designed to be highly durable, low-maintenance and affordable. We conclude from the data presented here that the Lifebox pulse oximeter also successfully achieves the required accuracy of the FDA standards.

Competing interests

Dr Dubowitz and Dr Lipnick are Founders and Directors of the non-profit charitable organisation 'Global Partners in Anesthesia and Surgery'. NIH funding received (K08 GM086511) and awarded to Jeffrey Sall (JWS).

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