Pulse oximetry in sickle cell disease

P Pianosi, T D Charge, D W Esseltne, A L Coates

Abstract
Patients with sickle cell disease usually have mild hypoxaemia and their oxyhaemoglobin dissociation curve is shifted to the right. It follows that oxygen saturation in sickle cell disease should be lower than normal. Most subjects in this clinic had normal oxygen saturation by pulse oximetry, however. To improve the understanding of this paradox, arterialised capillary oxygen tension (P02) and oxygen saturation were measured simultaneously with pulse oximeter in 20 children with sickle cell disease. In addition, the P02 at 50% haemoglobin saturation (P50) was calculated from the measured pulse oximetry in all 20 patients. It was found that saturation measured by pulse oximetry was, on the whole, similar to that calculated from the sampled blood. Individual deviations were not random, however, and were partly explained by differences in P50 values. It is concluded that pulse oximetry gives variable results in patients with sickle cell disease and should be used with caution to predict arterial saturation in this patient group.

The use of pulse oximetry is becoming more common in routine clinical practice with the advent of inexpensive, portable oximeters. This has allowed non-invasive measurement of oxygen saturation (SpO2) within 2% of that measured spectrophotometrically at oxygen saturation values > 75%.

Hypoxaemia has been reported in children with sickle cell disease. The arterial oxygen tension (PaO2) values in this study ranged from 8-64 to 11.30 kPa (65-85 mm Hg), which would normally correlate with saturations in the range 91-97%. The oxyhaemoglobin dissociation curve is known to be shifted to the right in sickle cell disease. Thus we were surprised to find that most patients with sickle cell disease in our clinic had normal (>=95%) SpO2 values, whereas intuitively we expected that most patients would have borderline or low values for SpO2. To improve our understanding of the assessment of pulmonary gas exchange in sickle cell disease, we sampled arterialised capillary blood in 20 patients, from which saturation was calculated, and compared this with saturation measured by pulse oximetry. We then compared SpO2 and P50 (P02 at 50% haemoglobin saturation) values to see if there was any relation between the magnitude of shift in the oxyhaemoglobin dissociation curve and SpO2. We also plotted the oxyhaemoglobin dissociation curve with data from four patients with sickle cell disease to verify that a curve shifted to the right would result in SaO2 ≥ 95% in a subject breathing ambient air with a normal alveolar-arterial oxygen gradient. Based on our clinical impression, we hypothesised that pulse oximeter saturation would overestimate true arterial saturation, and that this would be seen particularly in patients with the greater rightward shift (higher P50) in their oxyhaemoglobin dissociation curve, who physiologically should have lower oxygen saturation.

Subjects and methods
Venous blood was obtained from 20 patients with sickle cell disease at the time of a routine clinic visit. All were well and had not received a transfusion in the preceding three months. The haemoglobin concentration was measured by standard methods. The value of P50 was determined as follows. Five millilitres of heparinised blood were obtained and then divided into two equal aliquots. Each aliquot was placed into the cuvette of one of two tonometers (IL 237). With the water bath preheated to 37°C and kept constant throughout, a test gas was pumped through each cuvette at 400 ml/min. The test gases used were 5% carbon dioxide balance nitrogen and 5% carbon dioxide balance oxygen such that blood in one tonometer would be fully saturated while that in the other desaturated (co-oximeter So2 < 5%). After 15 minutes of blood-gas equilibration aliquots of blood were withdrawn from each cuvette in varying ratios such that total volume was approximately 0.5 ml. A few stainless steel pellets were added to the oxygen mixture and, with the outlet sealed, the syringe was shaken to ensure adequate mixing of saturated and desaturated blood. We avoided prolonged periods of desaturation in the process, or repeated deoxy-oxygenation cycles, as these have been shown to lead to irreversible biophysical changes in red cells with sickle haemoglobin (HbS). The blood was then analysed for pH, P02, and carbon dioxide tension (Pco2) (Radiometer ABL30) and oxygen saturation (Radiometer OSM2 Hemoximeter). The P02 value obtained was corrected to a standard pH of 7-40 using an IL P02 pH nomogram (Instrumentation Laboratory). The points obtained were then plotted using P50 on the abscissa and SaO2 on the ordinate. P50 (the P02 at 50% saturation) was determined using three to four points in the 40-60% saturation range by linear interpolation. Using a larger amount of blood from four of these patients the entire oxyhaemoglobin dissociation curve was plotted, fitting a sigmoid curve by eye, to eight to 10 data points for each patient. To obtain better resolution for curve fitting, two oxyhaemoglobin dissociation curves were constructed by combining P02 and So2 data from patients with similar P50 values. This was carried out to verify that the rightward shift in oxyhaemoglobin dissociation curve in our patient group. To validate our methodology, blood from two controls (HbAA) was also obtained for

Respiratory Medicine and Hematology Services, McGill University-Montreal Children's Hospital Research Institute P Pianosi T D Charge D W Esseltne A L Coates Correspondence to: Dr Paul Pianosi, CN-503, Children's Hospital, 840 Sherbrook Street, Winnipeg, Manitoba, Canada R3A 1S1. Accepted 6 January 1993
Figure 1  Plot of the oxyhaemoglobin dissociation curves for patients with sickle cell disease (open symbols, one shape for each patient) in (B) and (C). The curve derived from normal haemoglobin is shown for comparison (closed symbols) in (A). Note different abscissa for each plot (1 kPa=7·5 mm Hg).

comparison, as the P50 in healthy sea level inhabitants is well known.

A Nellcor N-200 pulse oximeter in the fast response, electrocardiogram synchronous mode was used to measure transcutaneous oxygen saturation. This was performed at rest with the patient seated on an exercise bicycle, and at the same time as PaO2 was obtained by arterialised capillary blood sampling from a fingertip during steady state exercise at 50% maximum work capacity. The hand was wrapped in a heated cloth for five minutes before sampling, the finger pierced with a lancet, and after wiping away the first drop, free flowing blood was collected into two or three capillary tubes. The tubes were immediately put on ice, and within 20 minutes, PaO2, PacO2, and pH were measured on a blood gas analyser (Radiometer ABL 3). Saturation SaO2 was calculated from this sample by the Kelman digital computer subroutine. Saturation data determined by pulse oximetry and calculated from arterialised capillary blood were compared by linear regression techniques. Differences between the two measures of saturation were then correlated with P50. Relationships between P50 and other variables were also explored by linear regression analysis, using a personal computer based program (Minitab).

Results

Figure 1 shows the sickle cell oxyhaemoglobin dissociation curve, together with one derived from controls. The P50 values for this subgroup of patients were 32·5 and 33·5 (fig 1B), and 35·0 and 35·2 (fig 1C). Comparison of the calculated saturation with the pulse oximeter derived saturation for the entire group of 20 patients is shown in fig 2A. The regression line for the comparison had a slope of 1·05, not significantly different from the line of identity. The relation just achieved statistical significance (p=0·04), however, as there was wide scatter about the line of identity (standard deviation 3·7% saturation). Differences between the two measurements of saturation are shown in fig 2B, plotted against P50. It can be appreciated that pulse oximetry tended to overestimate arterial saturation in patients with only a slightly right shifted oxyhaemoglobin dissociation curve, but tended to underestimate saturation in those with markedly right shifted curves.

The table shows the mean P50, haemoglobin, saturation, and PaO2 values for all 20 patients. There was an inverse correlation between P50 and haemoglobin concentration (r=0·48; p=0·006). Subjects with sickle cell disease had resting SpO2 values ranging from 82 to 100%,
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Clinical characteristics of the group of patients with sickle cell disease

<table>
<thead>
<tr>
<th>Haemoglobin (g/l)</th>
<th>$P_{50}$(mm Hg)</th>
<th>$S_{PO2}$ (%)</th>
<th>$S_{AO2}$ (%)</th>
<th>$P_{AO2}$(kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>100</td>
<td>94-9</td>
<td>95-5</td>
<td>10-26</td>
</tr>
<tr>
<td>Range</td>
<td>65-113</td>
<td>27-3-42.8</td>
<td>82-100</td>
<td>91-97</td>
</tr>
</tbody>
</table>

*Calculated $S_{AO2}$.

with only five less than 95% (94, 93, 93, 92, and 82%). The $P_{50}$ values of these five were 3-86 (29), 4.26 (32), 5.72 (43), 4.12 (31), and 5.45 (41) kPa (mm Hg) respectively. Looking at the data differently, three patients had markedly increased $P_{50}$ values (>5-3 kPa, 40 mm Hg), with $S_{PO2}$ measurements of 91, 92, and 82%, and calculated $S_{AO2}$ values of 96, 95, and 91%. As expected, there was no statistically significant relation between $S_{AO2}$ and $P_{50}$, but there was a significant relation ($p=0.003$) between $S_{PO2}$ and $P_{50}$, even after exclusion of the outlying point (fig 3).

Discussion

We have shown that, in general, pulse oximetry provides a reasonably accurate measurement of oxygen saturation in patients with sickle cell disease, but that its value is suspect in predicting a given subject’s arterial saturation. It is clear that results can be widely (≥4%) discrepant in some instances, with overestimates and underestimates of true arterial saturation observed. Furthermore, the magnitude and direction of the error are not random, and depend on $P_{50}$.

There are several possible explanations for the variable and sometimes conflicting data comparing pulse oximetry with measured arterial saturation, and for the paucity of lower $S_{PO2}$ values in our patient group. Jubran and Tobin reported inaccurate oximetry readings (>4% difference between saturation measured by a pulse oximeter and co-oximeter) were more common in black than in white patients. If fig 4 of their paper is examined, it is clear that pulse oximeter measurements were consistently above 90% whereas saturation co-oximeter values ranged from 78 to 97%. Skin pigmentation should not affect the $S_{PO2}$ values measured by the two wavelength pulse oximeter as the light beam ‘reads’ pulsatility in the absorption phenomenon. As pointed out by these workers, however, dark skin pigmentation may interfere with absorption at the wavelengths used in pulse oximetry. The possibility of inaccurate $S_{PO2}$ values in black subjects has also been shown during exercise and hypoxia. In that study the eight wavelength oximeter fared better than any two wavelength device, the latter generally overestimating true $S_{AO2}$. Another potential factor causing suspect $S_{PO2}$ measurements in sickle cell disease was emphasised in a review of non-invasive monitoring of blood gases. The scattering of the light emitted by the sensor as it passes through tissues depends on the geometry of the red blood cell. If this red blood cell geometry in the patient does not match that of subjects from whom the empirical calibration graph of the oximeter’s algorithm was derived (which is probable in patients with sickle cell disease), then significant measurement error may result.

We are not suggesting all pulse oximetry values are unreliable in patients with sickle cell disease. The large differences noted by Jubran and Tobin occurred in only 27% of their subjects. The clinical dilemma lies in deciding in which patients pulse oximetry is misleading, and in which patients it is reliable. This is not a trivial dilemma. It may mean as little as a patient receiving more oxygen than is actually needed. Alternatively, it may mean that a series of investigations into the cause of ‘desaturation’ is launched needlessly if oximetry alone is used to assess the adequacy of pulmonary gas exchange.

The right shift in the oxyhaemoglobin dissociation curve in anaemia, quantitated by $P_{50}$, is considered a compensatory mechanism whereby oxygen bound to haemoglobin with reduced affinity will be released more readily to the tissues where $P_{O2}$ is low. The $P_{50}$ value of our patients ranged from 3-46 to 5.72 kPa (26-43 mm Hg), and was inversely related to haemoglobin concentration, in agreement with previous studies. In some patients with anaemia, increased $P_{50}$ is due to the accumulation of 2,3-diphosphoglycerate (DPG) in the red cell. In sickle cell disease, it is the presence of HbS which reduces the affinity for oxygen, although the 2, 3-DPG concentration may actually be low. Whereas the magnitude of the difference between $S_{PO2}$ and $S_{AO2}$ was correlated with the haemoglobin concentration and $P_{50}$, stepwise multiple regression analysis showed that almost all the variance was explained by $P_{50}$. This leads us to speculate that the presence of HbS in the erythrocyte causes a peculiar dispersion pattern of the incident infrared light used by the two wavelength pulse oximeter, and this accounts for our findings.

We believe that the use of arterialised capillary $P_{O2}$ was valid, because the mean $P_{O2}$ of our patients was similar to that reported by Wall et al who measured resting arterial $P_{O2}$. Thus we do not feel that the calculated $S_{AO2}$ was biased by artificially low $P_{O2}$. Because of the shape of the oxyhaemoglobin dissociation curve, we would normally expect saturation to lie within a narrow range despite $P_{AO2}$ varying from 9-31 to 13-3 kPa (70-100 mm Hg). Thus pulse oximetry might be relatively insensitive to mild degrees of hypoxaemia, considering the precision of the pulse oximeter. Given that most patients with sickle...
cell disease have some degree of hypoxaemia and that nearly all have a right shifted oxyhaemoglobin dissociation curve, however, it was somewhat puzzling that a broader range of $\text{SpO}_2$ values in our patient group was not observed.

It is clear that a study comparing $\text{SpO}_2$ and arterial $\text{So}_2$ determined by co-oximeter in patients with sickle cell disease is warranted. Until a better understanding of the relation between pulse oximetry and true arterial saturation is found, periodic arterial blood gas sampling, especially at times of clinical pulmonary disease, would appear essential for pulse oximetry to be a useful tool in management of sickle cell disease.

Dr Pianosi was a fellow of the Canadian Cystic Fibrosis Foundation.