NON-INVASIVE ASSESSMENT OF PULMONARY OXYGEN EXCHANGE;
THE SaO_2 vs. PiO_2 SLIDE RULE. JG Jones.

Traditional indices of oxygen exchange

The quality of pulmonary oxygen exchange is assessed by the difference between the oxygen level in the arterial blood and in the inspired gas.

Arterial blood oxygen is defined by the oxygen partial pressure (PaO_2 in mmHg or kilopascals, kPa), or saturation (SaO_2 in %). These are measured using either an arterial sample, or a transcutaneous technique or pulse oximetry (SpO_2%). The oxygen in inspired gas is expressed either as a percentage or as the partial pressure of inspired oxygen (PiO_2 in mmHg or kPa). Air is virtually 21% oxygen and if one is breathing air then the 'fraction of inspired oxygen' - FiO_2 - is 0.21.

The oxygen concentration of air is constant at 21% throughout the earth's atmosphere; it does not vary with altitude. What changes is the barometric pressure and it is the pressure exerted by the oxygen we breathe that is the driving force behind the take up of oxygen by the blood. At sea-level atmospheric pressure is 101.325 kPa and 21% of this is due to the presence of oxygen. The partial pressure of oxygen at sea-level is therefore 21.28 kPa (i.e. 101.325 x 21/100 = 21.28). *Therefore, provided one is operating at approximately sea-level, it is reasonable to regard FiO_2 expressed as a percentage to be the same value as PiO_2 expressed as kPa.*

There are at least 5 indices of oxygen exchange used in Intensive Care units; PaO_2/FiO_2; PaO_2 /PAO_2 (ratio of arterial to alveolar oxygen pressure); $P[A\text{-}a]O_2$ (alveolar-arterial oxygen gradient- normally 1-2.5kPa); $P[A\text{-}a]O_2/PaO_2$ and finally the degree of right to left shunt, i.e. the proportion of shunt flow (Q_S) to the total blood flow (Q_T).

All are difficult to interpret when PiO_2 is changing, when transcutaneous PO_2 is used (long, 15-30s, response time) and particularly when there is reduced ventilation of perfused alveoli (reduced V_A/Q).[1] The V_A/Q is the balance of ventilation and perfusion of alveoli. If alveolar ventilation and perfusion are matched then V_A/Q is just less than 1 (i.e. 0.8). Hitherto a reduced V_A/Q was ignored because it was technically difficult to measure, particularly in infants, and the impairment of gas exchange was erroneously assumed to be entirely due to intrapulmonary shunt. This is poignant because the cardinal feature of bronchopulmonary dysplasia (BPD), for example, is a reduced alveolar surface area and attenuation of lung vasculature[2] giving a considerable reduction in V_A/Q as well as a fall in compliance and increase in PCO_2.

This section describes pulmonary oxygen exchange both in terms of shunt and of reduced V_A/Q (measured non-invasively) using a computerised slide rule. Most babies with oxygenation problems related to ventilation will have a mixture of these two problems. The response to oxygen supplementation will differ according to which of these two problems predominates. Those with a predominant shunt will be 'protected' from hyperoxia because a large increase in inspired oxygen will be needed to produce 'overdose'. However babies with a predominantly low V_A/Q will be at risk of both hypoxia and hyperoxia because small changes in inspired oxygen will produce large changes in P_AO_2.

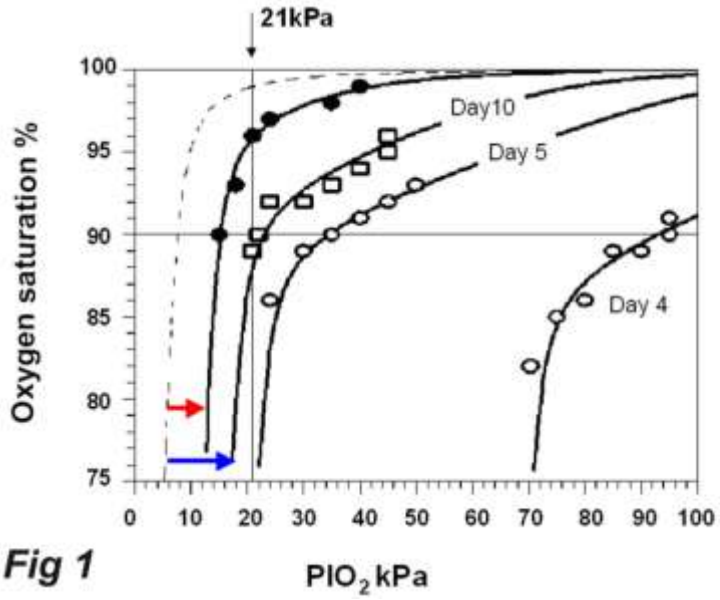


Fig 1

The SaO_2 vs. PiO_2 curve

Difficulties using traditional indices of oxygen exchange are resolved if PiO_2 is changed stepwise within agreed safe limits (even below 21 kPa) while pulse oximeter (SaO_2) readings are plotted against PiO_2. As we have established, at sea level an FiO_2 of 0·21 is (almost exactly) the same as a PiO_2 of 21 kPa. Not only does the SaO_2 vs. PiO_2 plot guide the appropriate choice of FiO_2 but it enables reduced V_A/Q and shunt to be derived from these two non-invasive measurements alone.

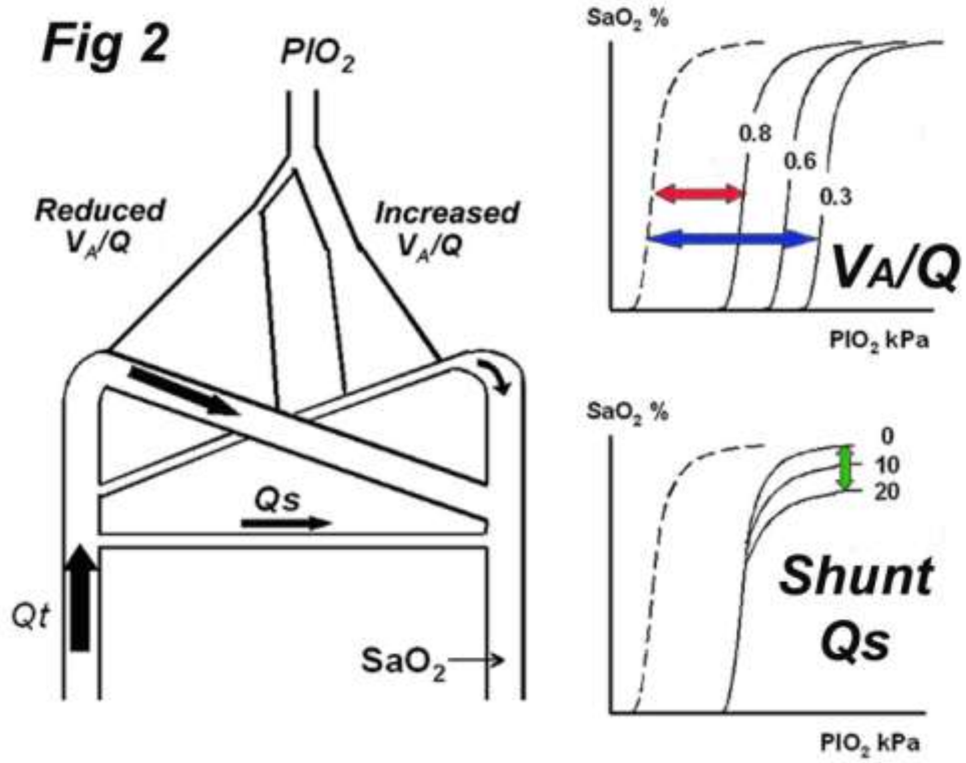
Such a plot (Fig 1) was produced in a neonate recovering from severe pulmonary failure.[3] The dashed line is the dissociation curve (DC) where PaO_2 is substituted for PiO_2. The vertical line indicates the PiO_2 of air. Closed circles show the normal SaO_2 vs. PiO_2 curve shifted about 6·5 kPa to the right of DC (red arrow). The curves extend beyond the data points because they are based on a mathematical model of gas exchange.

The infant described in Fig 1 was studied 4, 5 and 10 days after delivery. *The most obvious change is the very large shift to the right of the SaO_2 vs PiO_2 curve.* Thus on Day 4 the curve is shifted 67 kPa to the right and the infant could not tolerate a PiO_2 less than 70 kPa (i.e. equivalent to 70% oxygen at sea level). In fact 95% oxygen was needed to give an oxygen saturation of 90%. As the infant improves the curve moves to the left. But by Day 5, although greatly improved, the curve was still shifted 17·2 kPa to the right and the infant could not tolerate air breathing without becoming profoundly hypoxaemic. Despite further improvement by Day10 the curve was shifted 11·7 kPa to the right (blue arrow) and, when breathing air, there were wide oscillations in SaO_2 between 80-90%.

Deriving V_A/Q and Shunt from the SaO_2 vs PiO_2 curve

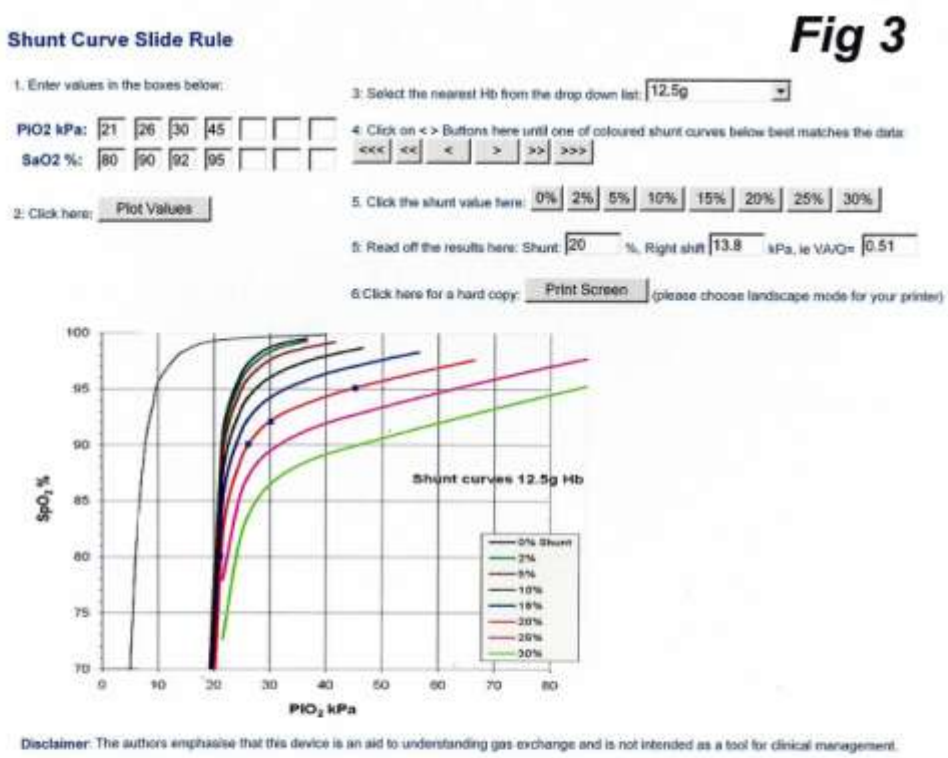
The shape of the SaO_2 v PiO_2 curve illustrates the effect of reduced ventilation of perfused alveoli (reduced V_A/Q) and of a Right to Left shunt (Qs – blood entering the arterial circulation without having the opportunity to take part in gas exchange). Reduced V_A/Q and increased Shunt often occur together but the SaO_2 vs PiO_2 curves have a characteristic shape in the two conditions (Fig 2). Note that a shunt implies alveoli that are perfused but not ventilated. "Reduced V_A/Q" means a V_A/Q ratio less than 0·8. When discussing oxygen exchange, alveoli with increased V_A/Q are ignored because they are poorly perfused with negligible effect on arterial oxygen saturation.

The top right panel of Fig 2 shows; the dissociation curve (dashed line); a SaO_2 vs PiO_2 curve representing a V_A/Q of 0·8 displaced to the right of the dashed line by a function of $PaCO_2$ (red arrow); a series of SaO_2 (or SpO_2) vs PiO_2 lines shifting to the right with decreasing V_A/Q stepwise from 0·8 to 0·3 (blue arrow). On this basis the infant shown in Fig 1 had a severe reduction in V_A/Q (<0·1) on day 4.



The lower right panel of Fig 2 shows the SaO_2 vs PiO_2 curve moving downwards (green arrow) with each increase in shunt from 0-20%. On this basis the infant shown in Fig 1 also had a very significant shunt on day 4.

A reduced V_A/Q increases $PaCO_2$ and lowers arterial oxygen saturation (SaO_2). The latter can be restored to normal by oxygen administration and in patients receiving supplemental oxygen a normal SaO_2 may conceal profound alveolar hypoventilation. Unlike reduced V_A/Q an increased shunt has negligible effect on $PaCO_2$ and SaO_2 increases only a little when inspired oxygen increases.



Deriving V_A/Q and Shunt with the SaO_2 vs PiO_2 slide rule

By varying PiO_2 in 3 to 5 steps the SaO_2 vs PiO_2 curve can be plotted out on the slide rule and the relevant Hb value entered to call down a cursor of coloured shunt curves. Fig 3 shows an infant with BPD [Ref 1 and http://www.noranaes.org/shuntcurves/]. The SaO_2 vs PiO_2 curves, corresponding to shunts ranging from 0-30%, are shifted sideways until one fits the data points and the shunt and shift read off. The reduced V_A/Q value is automatically displayed. By shifting the cursor to the right the effect of reducing V_A/Q is reproduced exactly.

The SaO_2 vs. PiO_2 curve provides a measure of:-

1. Shunt and reduction in V_A/Q (shift).
2. A graded response of impaired gas exchange to treatment.
3. The likelihood of hypoxaemia at any PiO_2. Hypoxaemia breathing air is likely with shifts greater than12 kPa at sea level and with shifts greater than 7·9 kPa in pressurised aircraft.
4. $PaCO_2$.
5. Hypoxic ventilatory drive.
6. The likelihood of hyperoxia.

The right shift of the SaO_2 vs. PiO_2 curve is often variable

The right shift from the dissociation curve may vary over days as shown in the infant in Fig 1. and over hours as shown in one of two adults in fig 4. These had continuous SaO_2 monitoring while breathing air overnight for 12-13 hours. Every 30 minutes the distribution of SaO_2 % values was plotted the baseline then moved up to plot the next 30min period. Subject RFC had a baseline shift of 7kPa and a 15% shunt. Overnight the peaks were centred around 94% saturation indicating a constant shift.

Subject LBW had a baseline shift of 12·2 kPa and 10% shunt. During the night the blunter peaks drifted down from a median of >90% to about 77% after 7½hrs, equivalent to a 14 kPa shift, then slowly recovering to about 85% at 13 hrs equivalent to a 13 kPa shift. An individual with a SaO_2 vs. PiO_2 that is almost a tangent to a vertical line representing PiO_2 will show large variability in SaO_2 for small changes in shift.

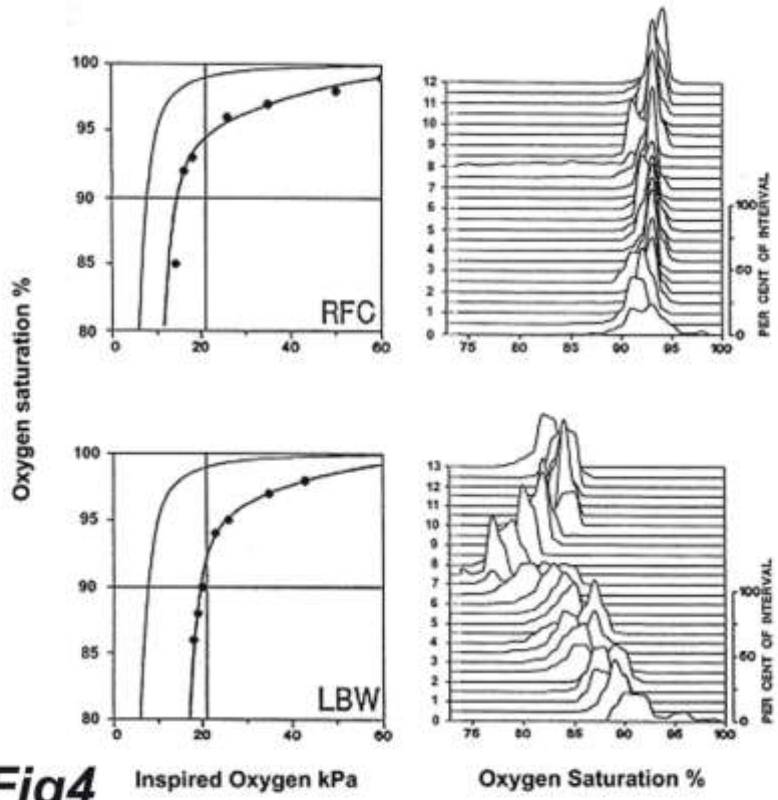


Fig4

The SaO_2 vs. PiO_2 curve, hyperoxia and P50

Two infants with different PiO_2 vs. SaO_2 curves are shown in Fig 5. One had a 20% shunt (**Shunt↑**) with a normal V_A/Q (0·8) in the remaining lung; the shunt moved the curve down. The other had a normal shunt (2%) but a low **V_A/Q↓** (0·3) in the remaining lung which shifted the curve to the right (Fig 5).

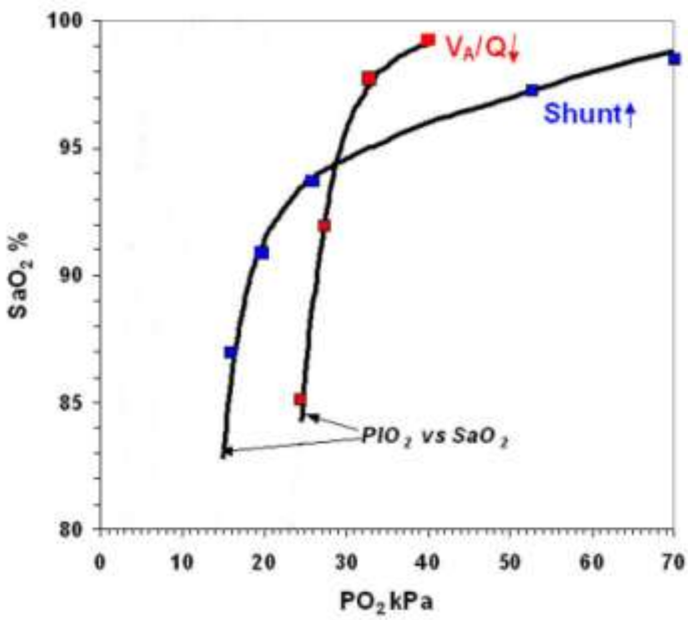


Fig 5

Both infants have an oxygen saturation of 94% at 28kPa PiO_2 where the curves cross (Blue arrow Fig 6).

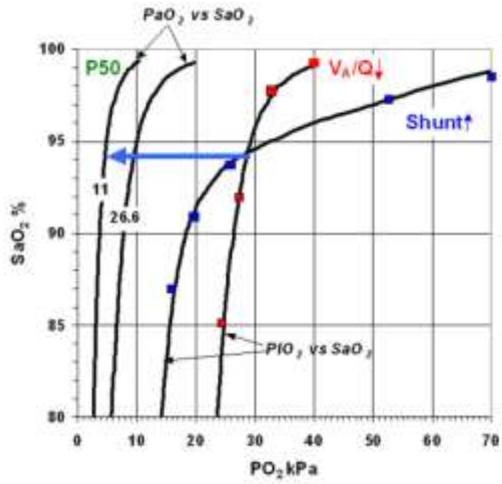


Fig 6

The arterial PaO_2 can be read off where the blue arrow crosses the dissociation curve (DC). Note the two Dissociation Curves in Fig 6. These curves are described by the P50 which is the partial pressure of oxygen at which haemoglobin is 50% saturated. The 26·6 mmHg P50 (or 3.55kPa) adult type curve gives a PaO_2 of 10 kPa and the foetal Hb curve with 11 mmHg P50 (or 1.47kPa P50) gives a PaO_2 of 5 kPa. These two P50 values represent the left and right ends of the Quine-Stenson data set.[5] The slide rule measures the shift in kPa from the position of the normal dissociation curve (P50 26·6mmHg) and calculates V_A/Q. In this example where V_A/Q is 0·3 the shift is about 17kPa.

Conclusions (see Fig 7)

The infant with an increased shunt (**Shunt↑**) whose curve is shown in fig 7 is "protected" from the effects of increased PiO_2 because inspired oxygen must be increased from 28% to 80% (i.e. a 50% oxygen increase) to give a 99% SaO_2. The other infant with **low V_A/Q** needed only a 12% oxygen increase, to 40%, to achieve the same SaO_2.

The lower the P50 the greater is the protection from increased SaO_2. Thus a SaO_2 of 99% gives a PaO_2 of 10 kPa if the P50 is 11 mmHg but 20 kPa if the P50 is of the adult type.

Infants with dominant low V_A/Q, because the curve is so steep, are more likely to have unstable SaO_2 values with small changes in inspired oxygen than infants with large shunts who have flatter curves. In Fig 7 the low V_A/Q infant has more difficulty avoiding hypoxaemia and hyperoxaemia than the large shunt infant.

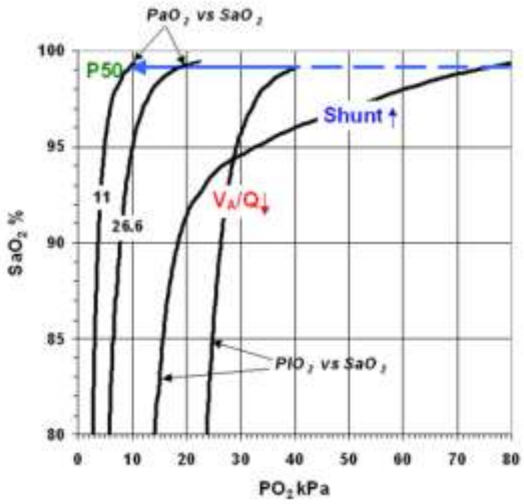


Fig 7

References

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2. Coalson JJ. Pathology of Bronchopulmonary Dysplasia. *Semin Perinatol*. 2006;**30**:179-184.
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