THE USE OF ISO-SHUNT LINES FOR CONTROL OF OXYGEN THERAPY

S. R. BENATAR, A. M. HEWLETT AND J. F. NUNN

SUMMARY

The concept of "virtual shunt" is presented as a practical means for determining the optimal inspired oxygen concentration for patients with hypoxaemia due to pulmonary venous admixture. The approach permits a reduction in the number of blood-gas analyses needed. Its limitations have been explored and its validity assessed from a series of 44 observations made on 4 patients.

Careful control of oxygen therapy is essential in the treatment of severe defects of arterial oxygenation. This is especially important in the type of case which is commonly treated by intermittent positive pressure ventilation. While aiming to maintain the arterial oxygen tension above the level required to avoid tissue hypoxia, it is also important to avoid unnecessarily high inspired oxygen concentrations, which might result in manifestations of pulmonary oxygen toxicity, or favour absorption collapse. There are three basic practical problems in the control of oxygen therapy:

1. Choice of an arterial oxygen tension (Pao2) which is acceptable or desirable for a particular patient.

2. Choice of an inspired oxygen concentration (FiO2) which will produce this arterial oxygen tension under the prevailing conditions in that patient.

3. The control of inspired oxygen concentration.

This paper is concerned with the second problem which, in an ideal situation, might be solved by continuous monitoring of arterial Pao2, with automatic or human feed-back to control the oxygen concentration in the inspired gas. This, however, is seldom feasible and we are proposing an alternative solution based on the fact that, if hypoventilation is excluded, the most important cause of arterial hypoxaemia is pulmonary venous admixture or shunting. Spread of ventilation-perfusion ratios (relative maldistribution) may also be a factor but, for practical purposes, it may be considered as though it were a shunt, albeit one which is negligible at high oxygen tensions, increasing as the Pao2 falls below 100 mm Hg.

In our approach we have considered two variables; FiO2, which is under the control of the medical and nursing staff, and Pao2, which is the value it is required to influence. The relationship between these variables is complex and non-linear, being governed by five main parameters: shunt (Qs/Qt), arterial/mixed venous oxygen content difference ((a-v)ΔCo2), haemoglobin concentration (Hb), arterial CO2 tension (PaCO2), and the displacement of the haemoglobin dissociation curve. The complexity of the relationship normally precludes quantitative assessment in the clinical environment.

We have attempted a simplification by graphical exploration of the relationship between the variables FiO2 and Pao2. The parameters Hb, PaCO2 and the displacement of the dissociation curve may be shown to be of relatively minor importance. Qs/Qt is clearly the most important factor and the relationship between FiO2 and Pao2 may be defined in terms of the value of Qs/Qt with graphical representation of iso-shunt lines (Nunn, 1966). The (a-v)ΔCo2 presents a difficulty, as the effect of this parameter is important but its value is usually unknown in the clinical situation. However, for a particular value of Qs/Qt, the relationship between FiO2 and Pao2 follows the same pattern with different values of (a-v)ΔCo2 although it is quantitatively different. We have, therefore, indicated the relationship between FiO2 and Pao2 in terms of the "virtual shunt" which we define as the shunt value if the (a-v)ΔCo2 were 5 ml/100 ml.

Derivation of the "virtual shunt" of a patient appears to offer a practicable basis for oxygen therapy in patients with major defects of arterial oxygenation and we present a graphical method for determination of "virtual shunt" and its subsequent use in therapy.


*Present address: Brompton Hospital, London S.W.3.
Requests for reprints should be addressed to Dr Nunn.
METHODS

Preparation of the Charts.

The relationship between cardiac output, physiological shunt and oxygen content of pulmonary end-capillary, arterial and mixed venous blood is indicated in the well-known shunt equation:

$$\frac{Qs}{Qt} = \frac{(Cc'_{O_2} - Ca_{O_2})}{(Cc'_{O_2} - Cv_{O_2})}$$

This may be rearranged so that:

$$Cc'_{O_2} - Ca_{O_2} = \frac{Qs}{Qt} \times (Ca_{O_2} - Cv_{O_2}) \times (1 - \frac{Qs}{Qt})(2)$$

$Pc'_{O_2}$ is assumed to be equal to $Pao_2$. $Ca_{O_2}$ and $Cc'_{O_2}$ can then be calculated from the corresponding $Po_2$ values. With an assumed value of 5 ml/100 ml for $(a-v)\Delta CO_2$ and the use of computer-produced haemoglobin dissociation curves (Hewlett and Coles, in preparation), graphs have been prepared relating $Pac_{O_2}$ to $Fio_2$ for various values of $Qs/Qt$. The coefficient of 1.34 was used for the oxygen combining power of haemoglobin. In practice this value is more often found than the theoretical figure of 1.39 which is based on the molecular weight of haemoglobin (Gregory, Hulands and Millar, 1972).

Figure 1A,B shows that the effect of changing the assumed value of $Pac_{O_2}$ from 40 to 25 mm Hg is to displace the iso-shunt lines to the left by the equivalent of 1-2% shunt. This effect is quantitatively similar at $Hb$ levels of 10 and 14 g/100 ml.

Figure 1c,d shows the effect of a change in $Hb$ from 14 to 10 g/100 ml at $Pac_{O_2}$ values of 40 and 25 mm Hg respectively. In both cases, the shape of the lower end of the iso-shunt curve is markedly changed. Haemoglobin concentration is the only parameter we have studied which causes any marked change in the shape (as opposed to the intercept) of the curves.
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\[ \text{Hb 10-14g\%} \]
\[ \text{Paco}_2 25-40 \text{ mm Hg} \]
\[ \text{a-O}_2 \text{ content diff. 5 vols\%} \]

**FIG. 2.** Composite diagram of the theoretical relationship between Paco\(_2\) and Fio\(_2\) for different values of shunt, with the shaded areas including all relationships illustrated in figure 1. This format is suitable for plotting results obtained on individual patients.

300

\[ \text{Hb 14g\%} \]
\[ \text{Paco}_2 40 \text{ mm Hg} \]

**FIG. 3.** Theoretical relationships between Paco\(_2\) and Fio\(_2\) for different values of shunt at two different values of arterial/mixed venous O\(_2\) content difference. Note that curves are displaced but their pattern is unaltered.
Figure 2 combines the limits of all the lines in figure 1 and indicates the possible range of each iso-shunt line within the limits of haemoglobin concentration 10–14 g/100 ml and \( P_{aCO_2} \) 25–40 mm Hg. All five figures have assumed an \((a-v)\Delta C_O_2\) of 5 ml/100 ml, and a respiratory quotient of 0.8.

If the various relationships are re-examined at an \((a-v)\Delta C_O_2\) of 8 ml/100 ml, there is a marked displacement of all iso-shunt lines to the right (fig. 3). The shapes of the curves, however, are unchanged: for example, the 10% iso-shunt line at the higher \((a-v)\Delta C_O_2\) is identical to the 15% iso-shunt line at the lower value. It follows that, as the shapes of the curves are unaltered, they can be used at any \((a-v)\Delta C_O_2\) to define the relationship between \( P_{ao2} \) and \( F_{IO_2} \) without the necessity to define the precise values for \( Qs/Qt \) and \((a-v)\Delta C_O_2\). The absolute \( Qs/Qt \) value for each curve will be dependent on the \((a-v)\Delta C_O_2\).

Thus, within the limits of applicability of the graph, a single pair of measurements of \( P_{ao2} \) and \( F_{IO_2} \) will identify a curve which we suggest can then be used to predict the iso-shunt curve of a patient may be expected to turn downwards at arterial \( P_{ao2} \) values below about 100 mm Hg; that is to say, the apparent virtual shunt value is increased in the lower range of inspired oxygen concentrations.

Use of the charts.

In the clinical situation it would be too laborious to prepare iso-shunt curves for individual patients, tailored to their own current values of haemoglobin, \( P_{aCO_2} \) and \((a-v)\Delta C_O_2\). We therefore propose that the standard graph (fig. 2) be used, with its bands to indicate the effect of variations in haemoglobin and \( P_{aCO_2} \) within the previously stated limits. Without knowing the patient's \((a-v)\Delta C_O_2\) the graph will indicate the virtual shunt.

The suggested procedure is to measure \( P_{ao2} \) at a known \( F_{IO_2} \) in the range 60–100% and then to derive the virtual shunt from figure 2. This curve is then followed down to the point at which the desired \( P_{ao2} \) is indicated; the required \( F_{IO_2} \) being read off the X axis. Greater confidence is obtained with two pairs of values and fine adjustment of \( P_{ao2} \) may be undertaken by subsequent measurement if considered necessary. In any case, use of the iso-shunt lines will substantially reduce the number of measurements of \( P_{ao2} \) which are required.

Test of validity of the charts.

We have tested the validity of the charts by recording simultaneous values of inspired oxygen concentration and arterial \( P_{o2} \) on patients, details of whose pathology is indicated in table I. Pairs of measurements were carried out at intervals of approximately 25 minutes allowing at least 20 minutes for stabilization on the new \( F_{IO_2} \). \( P_{ao2} \) was measured using a Servomex OA150 paramagnetic analyser calibrated with oxygen-free nitrogen and 100% oxygen. \( P_{ao2} \) was measured with a Radiometer electrode (type E5406) calibrated with oxygen-free nitrogen and air-equilibrated 30% glycerol (Hulands, Nunn and Paterson, 1970). \( P_{aCO_2} \) was measured with a Radiometer electrometer electrode (type E5306) and pH was measured with the Radiometer PHM electrode. Appropriate corrections were applied for the patient's temperature and for time delay between sampling and analysis (less than 10 minutes in all cases). Minute volume of ventilation was held constant during each series of measurement.

RESULTS

A series of paired measurements of \( P_{ao2} \) and \( F_{IO_2} \) were made on eleven separate occasions in 4 patients who were critically ill and required intermittent positive pressure ventilation in an intensive therapy unit (table I). In most cases, simultaneous values for \( P_{ao2} \) and \( F_{IO_2} \) followed iso-shunt lines reasonably closely, the majority of points being within \( \pm 2\% \) of the mean iso-shunt line (figs. 4–6). In two cases there was a marked rise in the virtual shunt values at the lowest value of \( F_{IO_2} \) and \( P_{ao2} \), and this is compatible with increased scatter ventilation/perfusion ratios. At values of \( P_{ao2} \) above 90 mm Hg the iso-shunt lines...
# TABLE I.

<table>
<thead>
<tr>
<th>Patient</th>
<th>F:\textsubscript{100} ×100</th>
<th>P\textsubscript{aO\textsubscript{2}} (mm Hg)</th>
<th>P\textsubscript{aCO\textsubscript{2}} (mm Hg)</th>
<th>pH</th>
<th>H\textsubscript{b} (g/100 ml)</th>
<th>Virtual shunt (%)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 aged 68 years</td>
<td>100</td>
<td>197</td>
<td>41</td>
<td>7.480</td>
<td>11.8</td>
<td>24</td>
</tr>
<tr>
<td>Diagnoisis:</td>
<td>83</td>
<td>125</td>
<td>71</td>
<td>7.480</td>
<td>11.8</td>
<td>24</td>
</tr>
<tr>
<td>Ischaemic heart disease</td>
<td>63</td>
<td>88</td>
<td>43</td>
<td>7.480</td>
<td>11.8</td>
<td>24</td>
</tr>
<tr>
<td>Chronic obstructive lung disease</td>
<td>53</td>
<td>75</td>
<td>36</td>
<td>7.480</td>
<td>11.8</td>
<td>24</td>
</tr>
<tr>
<td>Respiratory failure</td>
<td>42</td>
<td>65</td>
<td>100</td>
<td>7.480</td>
<td>11.8</td>
<td>24</td>
</tr>
<tr>
<td>No. 2 aged 69 years</td>
<td>87</td>
<td>320</td>
<td>38</td>
<td>7.502</td>
<td>14.6</td>
<td>15</td>
</tr>
<tr>
<td>Diagnosisis:</td>
<td>74</td>
<td>262</td>
<td>64</td>
<td>7.502</td>
<td>14.6</td>
<td>15</td>
</tr>
<tr>
<td>Bronchiectasis</td>
<td>64</td>
<td>184</td>
<td>54</td>
<td>7.502</td>
<td>14.6</td>
<td>15</td>
</tr>
<tr>
<td>Bronchopneumonia</td>
<td>46</td>
<td>120</td>
<td>21</td>
<td>7.502</td>
<td>14.6</td>
<td>15</td>
</tr>
<tr>
<td>No. 3 aged 63 years</td>
<td>98</td>
<td>317</td>
<td>98</td>
<td>7.480</td>
<td>15.5</td>
<td>18</td>
</tr>
<tr>
<td>Diagnosisis:</td>
<td>54</td>
<td>120</td>
<td>50</td>
<td>7.480</td>
<td>15.5</td>
<td>18</td>
</tr>
<tr>
<td>Myocardial infarct</td>
<td>100</td>
<td>309</td>
<td>50</td>
<td>7.480</td>
<td>15.5</td>
<td>18</td>
</tr>
<tr>
<td>Pulmonary oedema</td>
<td>70</td>
<td>145</td>
<td>50</td>
<td>7.480</td>
<td>15.5</td>
<td>18</td>
</tr>
<tr>
<td>No. 4 aged 70 years</td>
<td>99</td>
<td>220</td>
<td>99</td>
<td>7.512</td>
<td>14.0</td>
<td>23</td>
</tr>
<tr>
<td>Diagnosis:</td>
<td>80</td>
<td>125</td>
<td>80</td>
<td>7.512</td>
<td>14.0</td>
<td>23</td>
</tr>
<tr>
<td>Myocardial infarct</td>
<td>60</td>
<td>90</td>
<td>60</td>
<td>7.512</td>
<td>14.0</td>
<td>23</td>
</tr>
<tr>
<td>Pulmonary oedema</td>
<td>50</td>
<td>87</td>
<td>50</td>
<td>7.512</td>
<td>14.0</td>
<td>23</td>
</tr>
</tbody>
</table>

*Predicted values for P\textsubscript{aO\textsubscript{2}} are derived by interpolation of F:\textsubscript{100} into virtual shunt curve obtained from highest pair of F\textsubscript{100} and P\textsubscript{aO\textsubscript{2}} measurements.

†Virtual shunts derived from figure 2.
**Fig. 4.** Symbols ○ ● and ■ are the points obtained on three separate occasions in patient No. 2. Line ○ is from one occasion in which four estimations were performed on patient No. 4.

**Fig. 5.** Symbols △ ■ and ○ show three successive lines derived from patient No. 1 at approximately 3-weekly intervals. Note the improvement during each interval.
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450r Hb 10-14g%

P«

COi

25-40 mm Hg

\(\Delta \text{O}_2\) content diff. 5 vols% 

350

150

100

\(\text{FIG. 6. Lines derived on four separate occasions from patient No. 3.}\)

were closely followed and deviations from the mean iso-shunt line of a patient did not exceed 2%. On three of the lines the shunt appeared to be smaller at the lowest level of \(\text{Fi}_2\) and this anomaly can be explained by the fact that on this part of the graph small errors in measurement of \(P_{ao}\) can result in a fairly large error in the estimation of the shunt. The alternative explanation of changes in cardiac output seems less likely.

In the case of patient No. 1 the virtual shunt decreased over a 3-week period between the first and third lines, and was found to be a useful index for assessing progress and response to therapy.

DISCUSSION

Until a decade ago, oxygen toxicity was of interest mainly to respiratory physiologists or investigators involved in the study of special environments such as hyperbaric conditions and outer space. With the increased use of IPPV and improvement in intensive therapy, the magnitude of the problem of pulmonary oxygen toxicity has become of increasing concern to clinicians and has been the subject of considerable experimental work and pathological studies. The recent article by Winter and Smith (1972) comprehensively reviews all such work to date.

Unlike retrolental fibroplasia, which is related to increased \(P_{o2}\) in retinal arterial blood in neonates receiving high inspired concentrations of oxygen (Ashton, 1968), the development of pulmonary oxygen toxicity appears to be predominantly dependent on alveolar oxygen tension (Winter et al., 1967).

The now well recognized danger of prolonged administration of high concentrations of oxygen necessitates frequent blood gas analyses if "overdose" with oxygen is to be avoided. From a logistic point of view, this is both laborious and time consuming. The concept of virtual shunt and the use of iso-shunt curves, although not without limitations, offers the advantage of a rational and less laborious approach to the control of oxygen therapy in patients on IPPV in an intensive therapy unit. The approach is only applicable to patients whose hypoxaemia is due to pulmonary venous admixture, who have \(P_{co2}\) and haemoglobin values within the limits indicated in figure 2 and are in a relatively steady state. For control of \(P_{ao}\), it is not necessary to know the \((a-\varphi)\Delta C_{o2}\), although changes in this parameter will clearly influence the prognostic significance of changes in a patient’s virtual shunt.

Examination of factors such as \(Hb\), \(P_{aco2}\), and \((a-\varphi)\Delta C_{o2}\), which influence the slope and intercept of the shunt lines, reveals the limitations of the
method and from figure 2 it can be seen that inaccurate estimations of virtual shunt are most likely to be made at low values of Fio₂ in the presence of shunts greater than 25% as in this range the curves relating PaO₂ and Fio₂ are very close together. However, since the curves are also flat, large changes in Fio₂ will have little effect on PaO₂, which will always be less than 100 mm Hg under these conditions. With shunts of less than about 28%, the suggested procedure of making the initial paired measurement of Fio₂ and PaO₂ at high values of Fio₂ enable the virtual shunt line to be located with a degree of accuracy which seems adequate for clinical use.

Although derived values for the virtual shunt tend to be most consistent at arterial PaO₂ levels above 100 mm Hg, the accuracy of prediction of PaO₂ is similar throughout the range. If, from the table, the virtual shunt is derived from a single Fio₂ (the highest), actual values for PaO₂ at other values of Fio₂ are within 10% of the predicted value in 70% of cases, and within 20% in 91% of cases, the largest error being 32% (28 mm Hg). This would probably give better control of PaO₂ than could be obtained by intuitive selection of Fio₂, at least by those without considerable experience of the problem.

ACKNOWLEDGEMENT

We are indebted to Dr E. B. Raftery for permission to analyse and publish data obtained from his patients in the course of therapy. Dr S. R. Benatar was in receipt of an ICI Clinical Research Fellowship. Dr A. M. Hewlett was in receipt of a Wellcome Research Fellowship.

REFERENCES


