Arterial/alveolar oxygen tension ratio: a critical appraisal

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A critical analysis of the arterial/alveolar oxygen tension ratio (a/APO$_2$) is presented by rearranging the terms of the pulmonary shunt equation. The influence of the shunt and inspired oxygen concentration on a/APO$_2$ are illustrated. It is shown that, despite reports to the contrary, a/APO$_2$ varies with FIO$_2$, particularly at high shunt levels.

In recent years, the arterial/alveolar oxygen tension ratio (PaO_2/PAO_2), sometimes denoted a/APO$_2$, has developed a reputation as an index of gas exchange well-suited for use in pulmonary assessment and oxygen therapy. For example, while the alveolar/arterial oxygen tension difference (A-aPO$_2$) is known to depend strongly on the fraction of inspired oxygen (FIO$_2$),[1] this property has been reported to be absent for the a/APO$_2$, thereby rendering it an index of gas exchange less dependent on extrapulmonary factors.[2] In particular, the reputed stability of a/APO$_2$ across varying FIO$_2$ levels has formed the basis for two reports concerning its use to predict PaO$_2$ following changes in FIO$_2$.[3,4] Similarly, Peris *et al.*[5] found a/APO$_2$ to be useful "not only for predicting the arterial oxygen tension but also choosing the necessary oxygen supplementation." However, to date, it appears that a/APO$_2$ has only been examined empirically and that no study of the physiological factors affecting it determined from first principles has been reported. Such a study is presented here. It is demonstrated that a/APO$_2$ does, in fact, have some dependence on FIO$_2$, particularly at high levels of pulmonary shunt.

Key words

ARTERIAL/ALVEOLAR OXYGEN TENSION RATIO; a/APO$_2$; pulmonary shunt.

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Analysis

Pulmonary shunt is an excellent measure of oxygen transfer properties of the lung which has been studied widely. The pulmonary shunt equation is well known:

$$Qs/Qt = (C\acute{c}O_2 - CaO_2)/(C\acute{c}O_2 - C\bar{v}O_2)$$

However, for notational simplicity, we will denote Qs/Qt as Z. By algebraic manipulation of the shunt equation, as shown in the appendix, it is possible

Glossary

a/APO$_2$	– arterial/alveolar oxygen tension ratio
A-aPO$_2$	– alveolar/arterial oxygen tension difference (mmHg)
CaO$_2$	– arterial oxygen content (vol%)
$C\acute{c}O_2$	– end pulmonary capillary oxygen content (vol%)
$C\bar{v}O_2$	– mixed venous oxygen content (vol%)
$Ca\text{-}\bar{v}O_2$	– arterial/mixed venous oxygen content difference (vol%)
FIO$_2$	– fraction of inspired oxygen
Hb	– haemoglobin concentration (g/dl)
PaCO$_2$	– arterial carbon dioxide (mmHg)
PaO$_2$	– arterial oxygen tension (mmHg)
PAO$_2$	– alveolar oxygen tension (mmHg)
PB	– barometric pressure (mmHg)
PH$_2$O	– water vapour pressure (mmHg)
Qs/Qt (Z)	– pulmonary shunt fraction
R	– gas exchange ratio
SaO$_2$	– arterial oxygen saturation
$S\acute{c}O_2$	– end pulmonary capillary oxygen saturation
$S\bar{v}O_2$	– mixed venous oxygen saturation

to relate arterial oxygen tension to its influencing factors:

$$(1)\quad PaO_2 = P_AO_2-[Ca-\bar{v}O_2 \times Z/(1-Z) - 1.34 \times (S\acute{c}O_2-SaO_2) \times Hb]/0.0031$$

where P_AO_2 (mmHg) is the alveolar oxygen tension, $Ca-\bar{v}O_2$ (vol%) is the arterial/mixed venous oxygen content difference (= $CaO_2 - C\bar{v}O_2$), $S\acute{c}O_2$ is end-pulmonary capillary fractional saturation, SaO_2 is the arterial saturation and Hb is the blood haemoglobin concentration ($g \cdot dl^{-1}$). The alveolar gas equation is used to determine P_AO_2:

$$(2)\quad P_AO_2 = (P_B - P_{H_2O}) \times F_IO_2 - PaCO_2 \times [F_IO_2 + (1 - F_IO_2)/R]$$

where PB is the barometric pressure (assumed to be 760 mmHg), P_{H_2O} is the patient's water vapour pressure (assumed to be 47 mmHg), $PaCO_2$ is the arterial CO_2 tension (usually assumed to be 40 mmHg) and R is the gas exchange ratio (assumed to be 0.8).

The arterial/alveolar PO_2 ratio can thus be obtained by taking the ratio of equations (1) and (2) for specific choices of physiological variables. However, solving equation (1) is complicated by the need to introduce analytical relationships between P_AO_2 and $S\acute{c}O_2$, and PaO_2 and SaO_2. Kellman[6] has developed a nonlinear analytical expression relating oxygen tension and saturation given pH, PCO_2 and temperature. This relation was used to obtain both $S\acute{c}O_2$ estimates from P_AO_2 and SaO_2 estimates from PaO_2 with the assumed levels of pH, PCO_2 and temperature being the same in both cases. (The usual assumptions were pH = 7.4, PCO_2 = 40 mmHg, temperature = 37° C.) The commonly used simplifying assumption of setting $S\acute{c}O_2$ equal to unity was avoided to provide for accuracy under conditions of low barometric pressure. Unfortunately, even with the Kellman equation, equation (1) is not easily solved because we are dealing with the solution of a set of two nonlinear equations (i.e., equation (1) and Kellman's equation). In the case of this study a computer-based successive approximation method was employed to obtain a solution. This amounted to iteratively making successively more accurate estimates of PaO_2 levels which met both equation (1) and Kellman's equation. Equation (1) was solved in this way to an accuracy of 0.005 mmHg for various values of Hb, $Ca-\bar{v}O_2$ and F_IO_2.

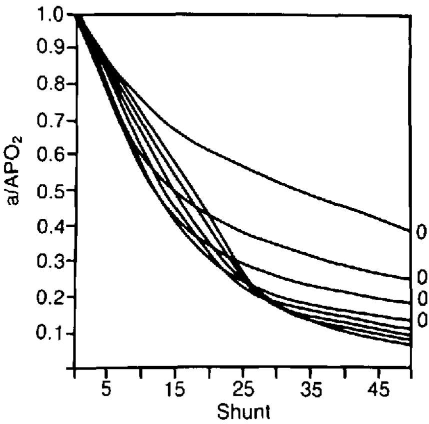

FIGURE Variation in arterial/alveolar PO_2 ratio (a/APO_2) with varying inspired oxygen levels (F_IO_2) and various levels of pulmonary shunt. Here Hb is $150\, g \cdot L^{-1}$. $Ca-\bar{v}O_2$ is 5 vol%, pH is 7.4, $PaCO_2$ is 40 mmHg, PB is 760 mmHg, R is 0.8, and body temperature is 37° C. Note the strong dependence of a/APO_2 on F_IO_2 at high shunt levels. The table presents some of this data in more detail.

Results

The figure shows how a/APO_2 varies with pulmonary shunt for F_IO_2 levels of 21, 30, 40, 50, 60, 70, 80, 90, and 100 per cent and with $Ca-\bar{v}O_2$ chosen to be 5 vol% and Hb set to $150\, g \cdot L^{-1}$. Here, for a given F_IO_2, a/APO_2 always decreases with shunt, while for a given shunt, a/APO_2 may vary in either direction with increases in F_IO_2. For example, for a patient with the above $Ca-\bar{v}O_2$ and Hb values and with a five per cent shunt, when breathing room air the a/APO_2 will be 0.848 while at an F_IO_2 of 40 per cent the a/APO_2 will drop to 0.740 and on 100 per cent oxygen the a/APO_2 will rise to 0.875. Similarly, with a 30 per cent shunt the a/APO_2 will be 0.525 on room air, 0.257 on 40 per cent oxygen and 0.163 on 100 per cent oxygen. As can be seen from the figure, variation of a/APO_2 with F_IO_2 seems to increase with shunt. In the table we present some of the data in more detail. Of particular interest is the observation that the ratio of maximum to minimum a/APO_2 values across the F_IO_2 values chosen increases with shunt, i.e., a/APO_2 varies more across F_IO_2 values with increasing shunt. Similar results were obtained for other haemoglobin and $Ca-\bar{v}O_2$ values. Clearly, the data suggest that a/APO_2 may vary considerably with F_IO_2 under

TABLE Detailed results of some of the data shown in the figure

Per cent shunt	*a/APO$_2$ on 21% oxygen*	*a/APO$_2$ on 100% oxygen*	*Minimum a/APO$_2$*	*Maximum a/APO$_2$*	*Max/min ratio*
5	0.848	0.875	0.740(40)	0.875(100)	1.18
10	0.745	0.738	0.536(40)	0.745(21)	1.39
15	0.670	0.587	0.386(50)	0.670(21)	1.74
20	0.612	0.425	0.281(60)	0.612(21)	2.18
25	0.565	0.268	0.207(70)	0.565(21)	2.73
30	0.525	0.163	0.155(90)	0.525(21)	3.39
35	0.489	0.117	0.117(100)	0.489(21)	4.18
40	0.455	0.096	0.096(100)	0.455(21)	4.74
45	0.422	0.083	0.083(100)	0.422(21)	5.08
50	0.389	0.073	0.073(100)	0.389(21)	5.33

Note that the variation of a/APO$_2$ across FIO$_2$ increases with shunt. Here Ca-$\bar{v}$O$_2$ was set at 5 vol% with a haemoglobin of 150 g·L^{-1}. Values in parentheses given are per cent FIO$_2$ values at which a maximum or minimum was found.

clinical conditions likely to be encountered in critically ill patients.

Discussion

The a/APO$_2$ ratio has been discussed widely in the critical care literature, but to date an analytical basis for understanding its behaviour with alterations of various physiological variables has not been available. Such an analysis based on the shunt equation is presented here. The widely held belief that a/APO$_2$ is relatively independent of FIO$_2$ is examined critically and is shown to be true only to a limited extent, particularly with large shunts. This is consistent with the later work of Gilbert *et al.*[7] who partially altered their original statements regarding alleged a/APO$_2$ stability with FIO$_2$ changes to point out that in critically ill patients a/APO$_2$ may change with FIO$_2$, although less so than A-aPO$_2$.

The above notwithstanding, it is the author's belief that the a/APO$_2$ remains a clinically useful index of gas exchange when its limitations are appreciated. Although the a/APO$_2$ is not independent of FIO$_2$, it can be shown to be less dependent of FIO$_2$ than the A-aPO$_2$, and on this basis alone it may be useful.

References

1 *Torda TA.* Alveolar-arterial oxygen tension difference: a critical look. Anaesth Intensive Care 1981; 9: 326–30.
2 *Gilbert R, Keighley JF.* The arterial-alveolar oxygen tension ratio. An index of gas exchange applicable to varying inspired oxygen concentration. Am Rev Respir Dis 1974; 109: 142–5.
3 *Hess D.* Prediction of the change in PaO$_2$. Crit Care Med 1979; 7: 568–9.
4 *Abizanda R, Lopez J.* The possibility of predicting PaO$_2$ following changes in FIO$_2$. Intensive Care Med 1981; 7: 247.
5 *Peris LV, Boix JH, Salom JV et al.* Clinical use of the arterial/alveolar oxygen tension ratio. Crit Care Med 1983; 11: 888–91.
6 *Kellman GR.* Digital computer subroutine for the conversion of oxygen tension into saturation. J Appl Physiol 1966; 21: 1375–6.
7 *Gilbert R, Auchincloss JH, Kuppinger M et al.* Stability of the arterial-alveolar oxygen partial pressure ratio. Effects of low ventilation-perfusion regions. Crit Care Med 1979; 7: 267–72.

Résumé

Une analyse critique du rapport de la tenson d'oxygène artérielle/alvéolaire (a/APO$_2$) est présentée en réarrangeant les termes de l'équation du shunt pulmonaire. Les influences du shunt et de la concentration d'oxygène inspirée sur le rapport a/APO$_2$ sont illustrées. Il est démontré que malgré les assertions contraires, les rapports a/APO$_2$ varient avec la FIO$_2$ particulièrement à des niveaux de shunt élevés.

Appendix

Derivation of equation (1):

$$Z\ (= Qs/Qt) = (C\acute{c}O_2 - CaO_2)/(C\acute{c}O_2 - C\bar{v}O_2)$$

Let

$$C\bar{v}O_2 = CaO_2 - Ca\text{-}\bar{v}O_2.$$

Then

$$Z = (C\acute{c}O_2 - CaO_2)/(C\acute{c}O_2 - CaO_2 + Ca\text{-}\bar{v}O_2)$$

or

$$C\acute{c}O_2 - CaO_2 = Z \times (C\acute{c}O_2 - CaO_2 + Ca\text{-}\bar{v}O_2).$$

Next, expressing oxygen contents in terms of oxygen saturation and oxygen tension, we have:

$$\begin{aligned}(S\acute{c}O_2 - SaO_2) \times Hb + (PAO_2 - PaO_2) \times 0.0031 \\ = Z \times [(S\acute{c}O_2 - SaO_2) \times Hb + (PAO_2 \\ - PaO_2) \times 0.0031 + Ca\text{-}\bar{v}O_2]\end{aligned}$$

or

$$\begin{aligned}[PAO_2 - PaO_2] \times (1 - Z) \times 0.0031 \\ + [S\acute{c}O_2 - SaO_2] \times Hb \times 1.34 \times (1 - Z) \\ = Z \times Ca\text{-}\bar{v}O_2\end{aligned}$$

or

$$\begin{aligned}PAO_2 - PaO_2 = [Ca\text{-}\bar{v}O_2 \times Z/(1 - Z) - 1.34 \\ \times (S\acute{c}O_2 - SaO_2) \times Hb]/0.0031\end{aligned}$$

or

$$\begin{aligned}PaO_2 = PAO_2 - [Ca\text{-}\bar{v}O_2 \times Z/(1 - Z) - 1.34 \\ \times (S\acute{c}O_2 - SaO_2) \times Hb]/0.0031.\end{aligned}$$