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Concentration and second gas effects: can the accepted explanation be improved?

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Summary

During induction with high inspired concentrations of nitrous oxide, net uptake of gas produces a contraction in volume and a concentrating effect. In turn, this results in concentration and second gas effects. Most explanations of these effects are based on the common "rectangle" diagram devised by Stoelting and Eger and contain several inconsistencies which are explored here in order to produce a more accurate description. It is shown that in the standard diagram gas uptake is incomplete, there is ambiguity over functional residual capacity (FRC), equilibration with blood is inadequately represented and there is no representation of recirculation of anaesthetic. Compensation for loss of volume may be by means of an increased inspired ventilation, decreased expired ventilation or reduction in lung volume. Numerous accounts in the literature (including those based on the standard diagram) focus on the former mechanism at constant FRC. This has produced an unbalanced picture in which it is often implied that extra gas is routinely drawn into the lungs to replace that taken up. Significant compensation by this means cannot occur, for example when a constant volume ventilator is used. In discussing concentration and second gas effects, it is necessary to give a balanced view of the alternative mechanisms of compensation or to revert, as above, to a simple statement of the principle of conservation of volume. (*Br. J. Anaesth.* 1997; **78**: 618–625).

Key words

Anaesthetics volatile. Anaesthetics gases, nitrous oxide. Pharmacokinetics, uptake. Pharmacokinetics, nitrous oxide. Pharmacokinetics, lung.

In the early stages of anaesthesia with high inspired concentrations of nitrous oxide, large volumes of gas, of the order of 1 litre min^{-1}, are transferred from lungs to blood.[1] The disappearance of volumes of this magnitude manifests itself in various ways. As gas volume uptake commences, it is associated with one or more of the following: increase in inspired ventilation, decrease in expired ventilation or reduction in lung volume.[2] Simultaneously, "concentration" and "second gas" effects are detectable.[3–7] The precise relationship between these two types of phenomena remains confused in the literature and is often stated in terms that imply that the large volumes lost by uptake are always compensated for by large volumes of gas being drawn in automatically from the anaesthetic apparatus. In this article, the process of gas volume uptake is examined in a variety of circumstances, in some of which extra inflow provides only part or none of the compensation. In addition, most explanations of the concentration and second gas effects are based on the common "rectangle" diagram devised by Stoelting and Eger[7] and involve several anomalies—these are explored and a more comprehensive version of the diagram developed.

Volume effects of gas uptake

In addition to being documented during anaesthesia with high inspired concentrations of nitrous oxide,[8] a reduction in functional residual capacity (FRC) occurs consistently in the anaesthetized patient under a wide range of unrelated conditions[9]: for example, during the use of halothane,[10] methoxyflurane[11] or isoflurane[12] in oxygen, or air–oxygen mixtures as the sole anaesthetic and during total i.v. anaesthesia (TIVA).[13] It is therefore reasonable to exclude a reduction in lung volume from the present discussion and limit our investigation to the effects of uptake on inspired and expired tidal volumes.

To simplify the discussion further, it is assumed that the patient is already anaesthetized by some other means, for example TIVA with 100% oxygen, the trachea intubated, connected to a non-rebreathing anaesthetic system and in a steady state at the time of introduction of nitrous oxide. Although differences exist between inspired and expired tidal volumes at steady state, owing to differences in the rates of exchange of oxygen and carbon dioxide, these are normally small and are also ignored, that is we assume a respiratory exchange ratio of 1.

Removal of gas volume by solution in lung tissue and blood may be reflected by a decrease in expired tidal volume or an increase in inspired tidal volume. Two extreme patterns are recognizable.[14–17] In one, the inspired tidal volume remains constant and equal

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to its value during the control period. To compensate for the loss of gas volume, the expired tidal volume decreases. However, it does not remain the same from one breath to the next, reflecting the difference in uptake from breath to breath. Eventually, nitrous oxide uptake begins to decrease and expired tidal volume gradually returns towards its original level.

This sequence of events is illustrated in figure 1A, in which the first pair of vertical lines represents inspired and expired tidal volumes in the control period. Successive pairs of lines represent inspired and expired tidal volumes during later breaths at regular intervals thereafter, for example every minute.

At the other extreme, we have a pattern in which expired tidal volume remains constant and equal to its value during the control period. Inspired tidal volume must therefore increase to compensate for the gas volume lost during the breath. Again, it does not remain constant from breath to breath but increases to a maximum and then gradually returns towards its control value, reflecting the time course of nitrous oxide uptake. This sequence of events is illustrated in figure 1B.

We refer to these as "constant inflow" and "constant outflow" situations. The term "constant" is used here in the sense that in one case, the inflow is constant from breath to breath and equal to its control value, while in the other it is the outflow that is constant from breath to breath and equal to its control value.

It is probable that neither extreme pattern is attainable clinically but a constant inflow is approximated by using a ventilator which cycles from inspiration to expiration after a preset volume has been delivered, and behaves as an atmospheric pressure generator during expiration, that is a constant volume ventilator.[14 16 17] A constant outflow is approximated during the use of a ventilator which includes a feedback loop based on end-tidal P_{CO_2},[18] and during spontaneous ventilation[14 16 17] if end-tidal P_{CO_2} is maintained constant and equal to its value in the control period.

If the subject is connected, in the control period, to a ventilator which cycles from inspiration to expiration at a preset pressure and acts as an atmospheric pressure generator during expiration, then inspired tidal volume increases to replace the gas volume lost by uptake during inspiration and expired tidal volume decreases to compensate for the continued loss of gas volume during expiration.[17] This situation is illustrated in figure 1C and is intermediate between the constant inflow and constant outflow extremes.

Nitrous oxide exchange, in common with that of other anaesthetic gases, involves an equilibration process between gas and blood.[19] At equilibrium, the concentration in blood = λ times the concentration in gas,[19] where λ = blood–gas partition coefficient. Thus, if λ is constant, the process obeys Henry's law, that is the dissolved concentration is proportional to partial pressure.[19] This is usually the case with inspired partial pressures of anaesthetics used clinically. In general terms we would therefore expect that the greater the inspired concentration of nitrous oxide, the greater the uptake and therefore the greater the difference between inspired and expired tidal volumes at any time during washin. This should apply irrespective of whether or not we are dealing with a constant inflow, constant outflow or intermediate situation.

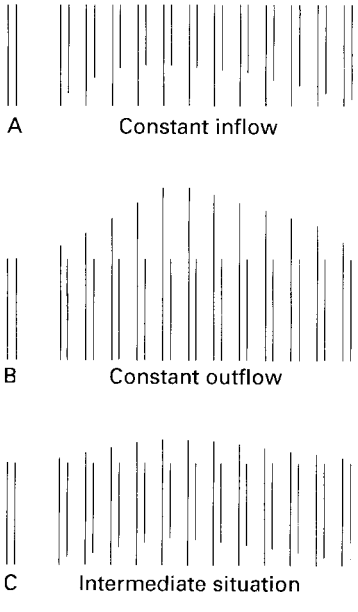

Figure 1 Schematic representation of different respiratory patterns seen during gas volume uptake with high concentrations of nitrous oxide: (A) constant inflow, (B) constant outflow, (C) intermediate situation. Each pair of vertical lines represents inspired and expired tidal volumes, respectively, for a particular breath. The left-most pair in each case represents inspired and expired tidal volumes for a breath during the control period. The remaining pairs represent later breaths at regular intervals (for example every minute) after introduction of a high inspired concentration of nitrous oxide.

Concentration and second gas effects

At the same time as the difference between inspired and expired tidal volumes finds expression in one or other pattern, it is possible to demonstrate that the higher the inspired concentration of nitrous oxide, the more rapidly the alveolar concentration approaches the inspired concentration.[3–5] This has been termed the "concentration effect". Any other gas administered simultaneously, for example 1% halothane, is also associated with a more rapid increase in alveolar concentration than would have been the case in the absence of nitrous oxide. This has been termed the "second gas effect".[6]

The standard diagram[7] used to discuss gas exchange in these circumstances is shown in figure 2. The figure consists of three rectangles which are described as representing events in a hypothetical lung. In the absence of a more detailed description, we interpret this to imply that the rectangles are a schematic representation of successive approximations to end-inspiratory alveolar gas volume, that is $FRC + (V_T - V_D)$. The hypothetical lung is filled initially with 80% nitrous oxide, 19% oxygen and 1% second gas. Uptake of half the nitrous oxide (without simultaneous uptake of oxygen or second gas) produces the situation shown in the middle rectangle, with a nitrous oxide concentration of

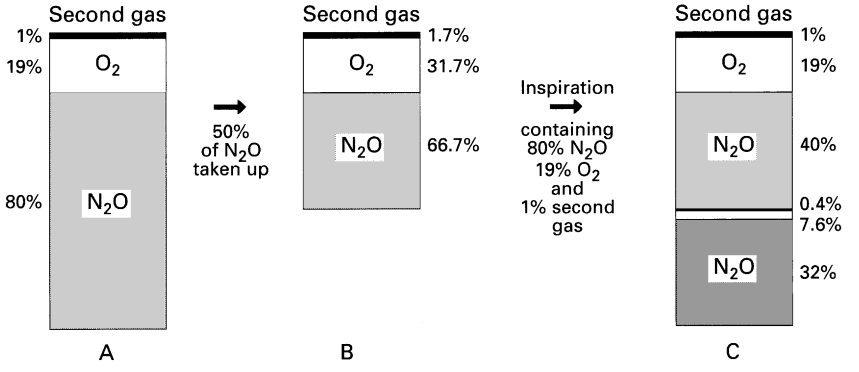

Figure 2 Standard diagram of a hypothetical lung used to discuss gas exchange during nitrous oxide uptake. Percentages are of the total volume in each rectangle. Reproduced with permission from Stocking and Eger.[7]

66.7%. To maintain lung volume, a further inflow of gas is necessary (B to C). This extra gas is shown having the same composition as in the first rectangle, and results in the concentration of nitrous oxide being increased further to 72%. The diagram or the associated explanation has appeared in numerous anaesthetic publications.[4 5 7 20–26]

Note that this treatment assumes that the second gas and oxygen are both insoluble (in the case of oxygen, a more realistic assumption[16] involves the exact replacement of oxygen uptake by carbon dioxide elimination, as assumed here).

Thus halving nitrons oxide initially present reduces its concentration from 80% to 72% instead of halving it to 40%. This argument has been used to explain the concentration effect by comparing this sequence with the situation where the initial nitrous oxide concentration is 1% and assuming again that half is taken up, but then replaced by almost pure oxygen,[5] so that nitrous oxide concentration is indeed almost exactly halved to 0.505%.

Meanwhile, the second gas which starts at a concentration of 1%, increases in concentration to 1.7% in the middle rectangle (a concentrating effect) and finally reaches 1.4% after being diluted by the increased inspiratory ventilation necessary to maintain lung volume (B to C). In figure 2, the solubility of the second gas has been assumed to be zero, and the increase in its concentration is seen to be caused by the concentrating effect. At the other extreme, if the second gas is very soluble, A to B takes the concentration from 1% towards zero, so that the concentrating effect associated with the uptake of nitrous oxide is much reduced. However, from B to C, the extra inflow restores the concentration of the second gas to at least 0.4%, so that the extra inflow seems to be more important.

Figure 2, as drawn, can also be interpreted as applying to a second gas which is soluble but with which the patient has been fully equilibrated before the carrier gas is changed from oxygen to a nitrous oxide-oxygen mixture, Thus there is little uptake of the second gas from A to B and its concentration is increased (although not quite to 1.7%) by the concentrating effect of the large uptake of nitrous oxide.

These comparisons have formed the basis of a hypothesis[7] that the further the second gas is from equilibration, the more its solubility determines which mechanism predominates—concentrating effect or extra inflow.

Note that the choice of the terms "concentration effect" and "concentrating effect" is rather unfortunate. The concentrating effect is an effect of uptake on concentration, whereas the concentration effect is an effect of concentration on uptake, that is on the rate of approach to equilibrium.

Deficiencies in the standard gas-exchange diagram

It may be shown that there are four deficiencies in figure 2: (1) gas uptake is incomplete; (2) there is ambiguity over FRC; (3) equilibration with blood is inadequately represented; and (4) there is no representation of recirculation of anaesthetic.

These deficiencies are now considered in turn.

INCOMPLETE UPTAKE

Although the gas present in the left-hand rectangle has been equilibrated in the sense that half the nitrous oxide has been removed, that in the extra inspired ventilation has not, a situation that is incompatible with the known behaviour of inert gas exchange.[19] This deficiency can be rectified by allowing half the nitrous oxide in the extra inspired ventilation to be taken up by blood. If we follow the reasoning used in the diagram, this results in a reduction in volume so that a further inspired ventilation is necessary and also has to be equilibrated. The process is depicted in figure 3, and continues for an infinite number of successively smaller steps to completion with a total uptake of nitrous oxide, and therefore a total extra inflow of inspired mixture, which is greater than that shown in figure 2, but still finite (267 ml instead of 160 ml).

The final concentrations of each agent may be deduced by inspecting each of the equilibrated portions, that is parts B, D, and F of figure 3 from which it can be seen that the final gas consists of an infinite number of portions each comprising 66.7% nitrous oxide, 31.7% oxygen and 1.7% second gas, so that this must also be the composition of the final gas mixture, that is the extra inflow is not associated with dilution and does not oppose the concentrating effect, as suggested previously. Note also that the representation of gas exchange as a stepwise process,

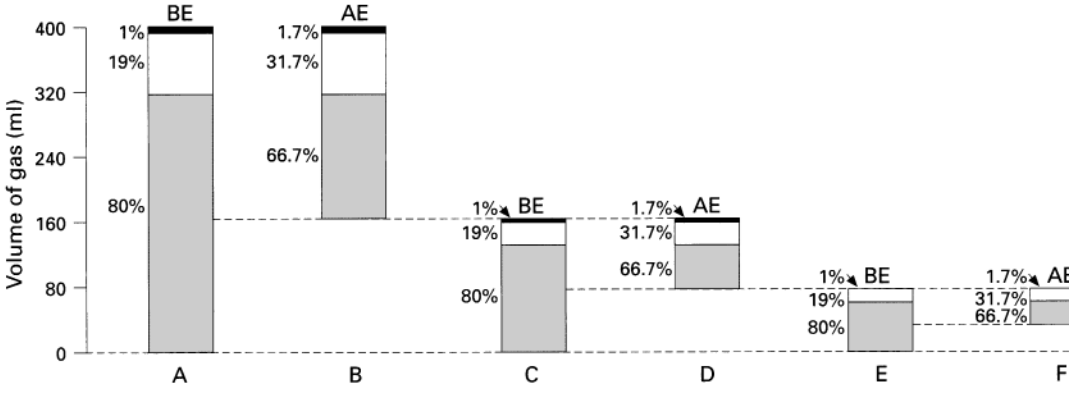

Figure 3 Multi-step method of completing nitrous oxide uptake (stippling = nitrous oxide, white = oxygen, black = second gas). A: 400 ml of gas are contained initially in the "lung". B: The situation after half the nitrous oxide has been absorbed. C: Extra gas is brought in to replace the absorbed nitrous oxide. D: Half the nitrous oxide is absorbed from the extra gas. E: This necessitates a further inflow of gas from which half the nitrous oxide is removed (F). The process is continued until uptake is complete. The gas in the "lung" then consists only of equilibrated portions, that is B+D+F+...BE = Before equilibration; AE = after equilibration. Total uptake of nitrous oxide, and therefore the total extra inflow of inspired mixture, is finite (267 ml) but greater than in figure 2 (160 ml).

as shown in figures 2 and 3, is purely schematic; in reality, absorption and replacement occur concurrently.

AMBIGUITY OF FRC

So far, figure 2 has been accepted as representing the events in the lungs as stated by the original authors.[7] This statement is now examined further.

The "lung" originally contains 80% nitrous oxide, 19% oxygen and 1% second gas. But this is also the composition of the inspired gas mixture (the "extra inspired ventilation" in the third rectangle). Such a situation applies only at the end of washin. However, when equilibration is complete, no further gas uptake occurs, contradicting the requirement that half the nitrous oxide be taken up.

An alternative interpretation is to regard the first rectangle in figure 2 as inspired tidal volume entering the lungs. The middle rectangle then represents what is left of this tidal volume after half the nitrous oxide has been taken up. There is, however, a problem with this interpretation, namely that when the inspired tidal volume enters the lungs and mixes with the gas in the FRC, the constituents of alveolar gas should appear in the expired tidal volume. For instance, if the subject had been breathing 100% oxygen during the control period, as assumed here, the concentration of oxygen in the expirate would be expected to be greater than shown in figure 2B.

This leaves us with a final interpretation of figure 2 in which the diagram is taken to represent an inspired tidal volume directly equilibrating with blood in the absence of FRC. Although this is an extraordinary assumption, it serves a useful purpose at this point in that it simplifies discussion of the volume effects of gas uptake and maximizes those effects by eliminating dilution of the inspired nitrous oxide in FRC.

Assuming zero FRC and uptake of half the nitrous oxide, we can now draw diagrams for the constant inflow and constant outflow situations. This has been done in figure 4. The first pair of rectangles represents the constant inflow, case; these are identical to the first two rectangles in figure 2. An inspired tidal volume of 400 ml (fig. 4A), comprising 80% nitrous oxide, 19% oxygen and 1% second gas loses half of the nitrous oxide (160 ml) as a result of gas uptake and results in the expired tidal volume shown in figure 4B. The second pair of rectangles represents the constant outflow case. To maintain expired tidal volume constant and equal to 400 ml, the inspired volume has to be sufficiently in excess of 400 ml to provide for the uptake of half the nitrous oxide (267 ml) that takes place in going from figure 4C to figure 4D. Note that the total uptake in the second pair of rectangles is equal to the sum of the parts in figure 3.

INADEQUATE EQUILIBRATION WITH BLOOD

In figure 4, the composition of the expired gas is the same, whether it is the inflow or outflow that is kept constant. This occurs because of the stated condition that "half the nitrous oxide be absorbed".[7] In reality, the fraction of nitrous oxide absorbed is not fixed but depends on equilibration between gas and blood, in accordance with Henry's law.[19] When this is allowed for, we obtain the situation shown in figure 5. Here we have assumed for convenience that each breath equilibrates with 400 ml of blood. λ for nitrous oxide has, for simplicity, been assumed to equal 1 so that the concentrations of nitrous oxide must be the same in gas and blood at equilibrium. It has also been assumed that recirculation of anaesthetic has not yet occurred so that initially the blood contains no nitrous oxide. As before, the second gas and oxygen are assumed to be completely insoluble.

It can be seen that, after equilibration, constant inflow and constant outflow patterns are associated with different concentrations of each gas. In particular, in the constant outflow case, a larger volume of nitrous oxide enters the blood than in the constant inflow case (267 ml *vs* 221 ml), although this represents a smaller fraction (40% *vs* 55.3%) of an increased inspired volume (667 ml *vs* 400 ml). As a result, the concentration in blood is greater in the constant outflow case (66.7 ml% *vs* 55.3 ml%), that is equilibration is more advanced.

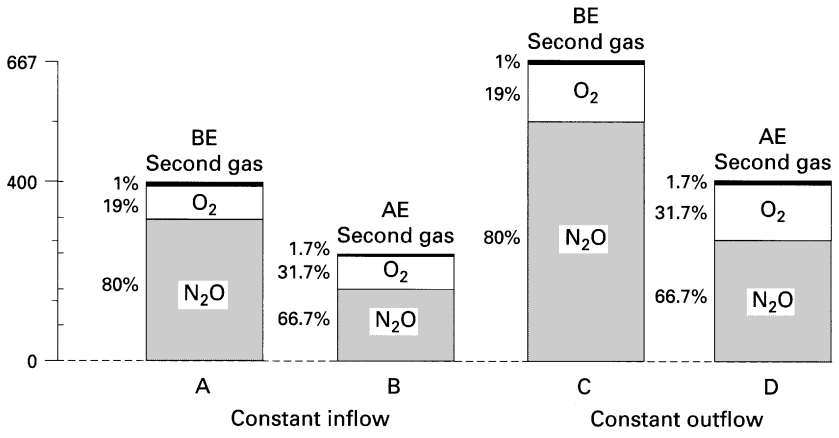

Figure 4 Constant inflow and outflow cases before and after uptake. A–B: Inspired tidal volume is kept constant and equal to 400 ml. C–D: Expired tidal volume is kept constant and equal to 400 ml. BE = Before equilibration; AE = after equilibration. The gradations on each side of the *Y*-axis occur at intervals of 20% of the inspired tidal volume for each case, that is at intervals of 80 ml for the constant inflow case and 133.3 ml for the constant outflow case.

Each of the three gases in figure 5 has been subjected to a concentrating effect. To see this in relation to nitrous oxide it is helpful to distinguish, before equilibration, between nitrous oxide destined for absorption and that destined to remain unabsorbed. This has been done by using different densities of stippling. Thus the black areas in figures 5A and 5C represent nitrous oxide destined to be absorbed. The unabsorbed nitrous oxide is seen to increase its concentration from 24.7% to 55.3% in the constant inflow case and from 40% to 66.7% in the constant outflow case. The increase in concentration of each of the three gases is equal to the quotient of the initial and final gas volumes.

Concentration and second gas effects are both demonstrable in terms of figure 5. The second gas effect is obvious. Its cause, a concentrating effect associated with absorption of nitrous oxide, is also obvious. To demonstrate the concentration effect it is necessary to consider what would be different with a lower inspired concentration.

If the inspired gas had contained only 1% nitrous oxide (4 ml in the constant inflow case) then after equilibration with blood there would be 2 ml of nitrous oxide in 400 ml of blood (0.5 ml%) and 2 ml in 398 ml of gas (0.502%). Thus there would be negligible contraction of volume and a negligible concentrating effect. The result would be almost identical in the constant outflow case. In these circumstances, blood comes into equilibrium with only half the inspired concentration. On the other hand, at a high inspired concentration of nitrous oxide (80% in fig. 5), there is a marked contraction in volume, a marked concentrating effect and blood

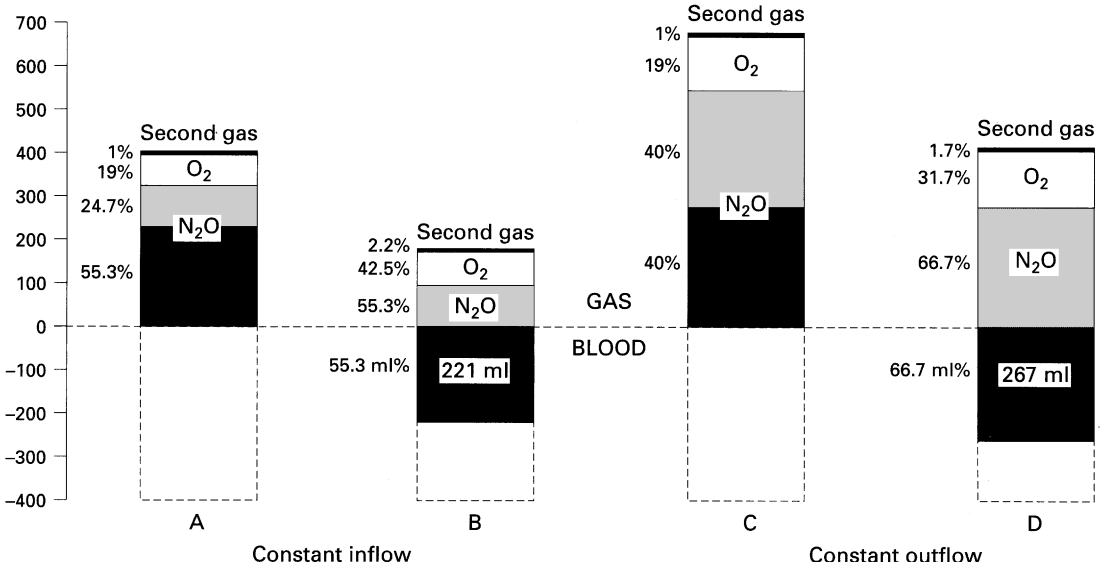

Figure 5 Constant inflow and outflow cases before and after equilibration with blood. A–B: Inspired tidal volume is kept constant and equal to 400 ml. C–D: Expired tidal volume is kept constant and equal to 400 ml. The *X*-axis represents the gas–blood interface across which equilibration occurs. In A and C, the area outlined by the dashed line on the blood side of the gas–blood interface represents the 400 ml of blood, initially free of nitrous oxide, to be equilibrated with gas. For simplicity, λ has been set to 1. The black area = nitrous oxide destined for absorption, the stippled area = nitrous oxide destined to remain unabsorbed. The volumes of gas in A, B, C and D are 400, 179, 667 and 400 ml, respectively.

comes into equilibrium with much more than half the inspired concentration: $(55.3/80) \times 100 = 69\%$ for the constant inflow case and $(66.7/80) \times 100 = 83\%$ for the constant outflow case. Thus a high inspired concentration leads to uptake of a larger fraction of the inspired volume and hence to a more rapid approach to equilibrium, especially in the constant outflow case, but even when conditions are such that Henry's law leads to half the nitrous oxide being taken up (C to D in fig. 5), the final concentration is 66.7%, not 72%, as in figure 2.

NO REPRESENTATION OF RECIRCULATION OF ANAESTHETIC

In figure 2, there is no representation of venous return and the associated recirculation of anaesthetic. Thus figures 2–5 each represents a "snapshot" of events before recirculation of anaesthetic. These deficiencies may be rectified and FRC incorporated simultaneously by reverting to a comprehensive computer model of anaesthetic uptake. When this is done, for example with the electrical analogue of Mapleson, it can been shown[16] that the constant outflow case is indeed always at a more advanced stage of equilibration during washin.

It is also possible to incorporate a non-zero FRC and recirculation of anaesthetic into the rectangle diagram. This has been done for the constant inflow case in figure 6 which is drawn for some arbitrary point during washin.

The diagram follows the same sequence as the mathematical model from which the existence of the concentration effect was first predicted,[3] that is instantaneous inspiration (fig. 6A) followed by complete mixing between the inspired tidal volume and the gas in FRC (fig. 6B), followed by equilibration with blood (fig. 6C), followed by separation into FRC and gas destined for instantaneous expiration (fig. 6D).

Using similar arguments to those used in relation to figure 5, it is possible to demonstrate the occurrence of concentration and second gas effects. Comparing figure 6 with the constant inflow case in figure 5, it can be shown that the reduction in gas volume for the breath decreases from 221 to 120 ml in absolute terms and from 55.3% to 5% as a percentage of the initial gas volume. This occurs because dilution of nitrous oxide in FRC and appearance of gas in the venous return both act to reduce the pressure gradient favouring nitrous oxide absorption. Accordingly, the concentrating effect is significantly reduced so that both concentration and second gas effects are reduced in magnitude, for example 35 ml% nitrous oxide in blood in figure 6 instead of 55.3 ml% as in figure 5, and 0.614% second gas in the gas phase instead of 2.2%.

Of course, the values 0.5%, 30%, 69.5% in FRC and 5 ml% in blood in figure 6A are all assumed. But whatever they are in practice at the beginning of a particular breath, a similar argument applies. The same is true if we use the constant outflow case and also if FRC is allowed to change in figure 6D instead of, or as well as, tidal volume. This last result should surprise no one as the principle of conservation of volume requires only that in the presence of net gas uptake, there must be a contraction in volume and a concentrating effect; maintaining lung volume is a convenient assumption in both the constant inflow and constant outflow models and is implied in the current treatment by the steady state condition with TIVA and 100% oxygen. Explanations of the concentration and second gas effects based on the relative solubilities of nitrous oxide and nitrogen merely restate the principle of conservation of volume in terms of the contributions of individual gases.

A one-sided picture of gas exchange

An unfortunate consequence of the widespread use of

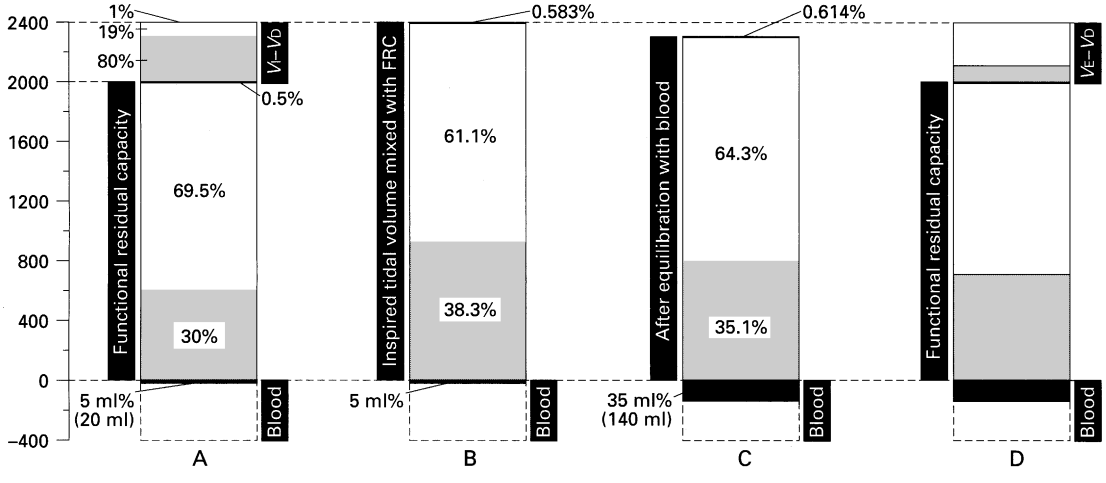

Figure 6 Constant inflow case with FRC and recirculation of anaesthetic. Single respiratory cycle during washin of nitrous oxide. An inspired mixture of 1% second gas (black), 19% oxygen (white) and 80% nitrous oxide (light shading) is used with a non-rebreathing system. The *Y*-axis shows the volume of gas or blood (ml). A: From top down, 400 ml of inspired gas mixture ($V_I - V_D$); FRC 2 litre comprising 0.5% second gas, 69.5% oxygen and 30% nitrous oxide; 400 ml of blood for equilibration containing 20 ml of recirculated nitrous oxide (black area). B: After complete mixing of inspired gas with FRC. C: After equilibration of gas with 400 ml of blood ($\lambda = 1$ for nitrous oxide and 0 for oxygen and the second gas). Dissolved nitrous oxide is shown as black. D: From top down, expired alveolar tidal volume ($V_E - V_D$) = 280 ml, FRC (still 2 litre) and blood, after equilibration.

figure 2 in texts on anaesthetic uptake is the implication that further gas is sucked routinely into the lungs during induction with high inspired concentrations of nitrous oxide. This concept has been expressed in various terms by different authors.[2 4 6 20 22–35] Although some accounts have not appealed to this phenomenon (e.g. Nunn[9]), or have used diagrams other than the standard diagram to help explain concentration and second gas effects (e.g. Hull[2]), the large number which have done so have conferred legitimacy on the underlying proposition.

There are three important aspects of these explanations with the emphasis varying from author to author: (i) gas is automatically drawn into the lungs to replace the volume loss caused by uptake, (ii) this is because otherwise lung volume would shrink, (iii) replacement is inevitable and beyond the control of the anaesthetist.

The problem with these descriptions is that they are limited in scope and fail to consider the alternative volume effects of gas uptake. Thus we can see from figure 1 that when authors write of an extra inspired ventilation[3 4 7 26] they are actually referring to the constant outflow case, in which an extra ventilation is readily identifiable. However, this requires not only constant lung volume but also constant expired ventilation, a point that is not usually stated explicitly.

Moreover, the implication that the anaesthetist has no control over the influx of this extra gas is demonstrably incorrect.[17] The anaesthetist decides whether or not respiration is to be spontaneous, and the type of ventilator to be used in the latter case. Ultimately, it is therefore the anaesthetist who decides whether there is an extra inspired ventilation, decreased expired ventilation or a combination of the two. Note also that in cases where a constant volume ventilator has been used,[7 29 31] extra inspired ventilation should never have come into consideration.

The preoccupation with the constant outflow case means that quantitative problems have often been cast solely in these terms to the exclusion of all other possibilities. The solutions obtained have not necessarily been universally applicable. For example, the concentration effect can be mimicked mathematically by a reduction in solubility.[16] One report of this property[36] was limited to the constant outflow case and overlooked an alternative mathematical expression that applies in the constant inflow case. Expressions for both cases were deducible in the original demonstration of this property.[16]

Balancing the ledger

The merit of the standard diagram (fig. 2) is that it gives some indication of how the concentration and second gas effects arise, when previously they emerged only from the correct application of the principle of conservation of volume in a computer program[3 4] or in an electrical analogue.[16] As such the diagram has probably helped innumerable students to gain some insight into these effects.

The disadvantage of the standard diagram is that numerous anomalies appear when it is examined closely: implied assumption of zero FRC; omission of uptake from the additional inspired gas; absence of any consideration of the process of equilibration with blood, and hence of the influence of recirculation; and restriction to the case of constant FRC, constant outflow.

For teaching purposes, simple qualitative models are often ideal, as long as they do not materially mislead the student. Figure 2 implies that an extra inflow of gas must be associated with a diluting effect, a proposition that is challenged in figures 3 and 4. The extent to which it is worth introducing the successive corrections contained in our figures 3–6 is a matter of judgement, although we believe that they should be mentioned. In addition, it seems regrettable that most of the accounts of the concentration and second gas effects based on figure 2 deal only with the constant outflow case at constant FRC. Although two authors[2 21] make some passing reference to alternative circumstances such as the constant inflow case, their detailed account is solely of the constant outflow case, typical of spontaneous breathing, which tends to reinforce the impression of the inevitability of extra gas being "sucked in" to replace that taken up. Indeed, one of the present authors must plead guilty to this in one of his publications![37]

To the best of our knowledge, figures 3–6 have not appeared previously in the anaesthetic literature. We believe that they extend the understanding of the concentration and second gas effects. Figure 6 certainly mirrors the steps of Eger's mathematical model more accurately than figure 2 but a second diagram is then needed to demonstrate the constant outflow case. As a bare minimum, we believe that explanations should include the statement that the net uptake of gas produces a contraction in volume which inevitably leads to concentration and second gas effects, regardless of whether compensation for uptake is by extra inflow, reduced outflow, decreased lung volume or a combination of the three.

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